# ROTARY AND MOTOR CONVERTERS

## A SELECTION OF

# LOCKWOOD'S MANUALS

| | Net |
|---|---|
| Alternating Currents. LARNER | 6s. 6d. |
| Aluminium Repairing. PLATT | 3s. 6d. |
| Art of Building. ALLEN | 6s. 6d. |
| Bees for Pleasure and Profit. SAMSON | 3s. 6d. |
| Boot Repairing. LORD | 5s. 6d. |
| Brass Founders' Manual. GATES | 5s. 6d. |
| Brick and Tile Manufacture. SEARLE | 7s. 6d. |
| Bricklaying. HAMMOND | 2s. 6d. |
| Brickwork. WALKER | 2s. 6d. |
| Builders' Accounts. KEEN | 5s. 6d. |
| Builders' Arithmetic. DOBSON | 2s. 6d. |
| Butter and Cheese. THOMSON | 4s. 6d. |
| Cabinet Maker's Guide. BITMEAD | 3s. 6d. |
| Carpentry and Joinery. TREDGOLD | 6s. 6d. |
| Chemistry (Elements). BASSETT | 5s. 6d. |
| Chemistry (Practical). MARTIN | 2s. 6d. |
| Clock Repairing and Making. GARRARD | 6s. 6d. |
| Coal Mining. COCKIN | 6s. 6d. |
| Colour in Advertising. KNIGHTS | 5s. 6d. |
| Colour Mixing and Paint Work. CARY | 2s. 6d. |
| Commercial Poultry Farming. TOOVEY | 6s. 6d. |
| Cotton Industry. CRABTREE | 6s. 6d. |
| Crop Production. HEPBURN | 7s. 6d. |
| Damp Walls. BLAKE | 8s. 6d. |
| Decorator's and Renovator's Assistant | 2s. 6d. |
| Efficient Boiler House. SIMMONS | 5s. 6d. |
| Electric Light Fitting. URQUHART | 5s. 6d. |
| Electrical Engineering. ALEXANDER | 3s. 6d. |
| Electrical Horology. LANGMAN | 7s. 6d. |
| Electro-Plating. WATT | 5s. 6d. |
| Enamelling on Metal. MILLENET | 6s. 6d. |
| Engineering Drawing. MALDEN | 8s. 6d. |
| Engineers' Measuring Tools. PULL | 4s. 6d. |
| Engineers' Screw Cutting. PULL | 2s. 6d. |
| French Polishing and Enamelling. BITMEAD | 2s. 6d. |
| Fretcutting. MAKINSON | 2s. 6d. |
| Garden Receipts. QUINN and OWEN | 2s. 6d. |
| Gasfitting and Appliances. BRIGGS | 2s. 6d. |
| Gas Meters. GILBERT | 6s. 6d. |
| Geometry for Technical Students SPRAGUE | 7s. 6d. |
| Goldsmith's Handbook. GEE | 1s. 6d. |

LONDON: CROSBY LOCKWOOD & SON

# ROTARY AND MOTOR CONVERTERS

A HANDBOOK FOR OPERATORS AND ATTENDANTS

BY

ERNEST F. SMITH



LONDON
CROSBY LOCKWOOD AND SON
STATIONERS' HALL COURT, E.C.4
1926

# LOCKWOOD'S MANUALS—*continued.*

| | Net. |
|---|---|
| Grading Dairy Produce. THOMSON | 6s. 0d. |
| Handrailing and Staircasing. COLLINGS | 3s. 6d. |
| House Painting, Graining, etc. DAVIDSON | 7s. 6d. |
| Illuminating and Missal Painting. WHITHARD | 6s. 0d. |
| Land Ready Reckoner. ARMAN | 4s. 0d. |
| Lathe Work. HASLUCK | 6s. 0d. |
| Laundry Chemistry. HARVEY | 4s. 0d. |
| Letter Painting Made Easy. BADENOCK | 2s. 0d. |
| Location of Mineral Fields. HADDOCK | 9s. 6d. |
| Marble Decoration. BLAGROVE | 3s. 6d. |
| Mass Production Equipment. GATES | 7s. 6d. |
| Mechanical Dentistry. HUNTER | 6s. 0d. |
| Metal Plate Work. BARRETT | 3s. 6d. |
| Mining Calculations. O'DONAHUE | 3s. 6d. |
| Motor Car Mechanism and Management. SHEPHERD | 4s. 6d. |
| Motor Tyres. FERGUSON | 3s. 6d. |
| Papermaking. CLAPPERTON | 7s. 6d. |
| Pattern Maker's Handybook. HASLUCK | 2s. 6d. |
| Photogravure. BENNETT | 5s. 0d. |
| Physics and Chemistry of Mining. BYROM | 6s. 0d. |
| Pigs and Bacon Curing. DAVIES | 4s. 6d. |
| Plastering. KEMP | 3s 0d. |
| Plumbing (Two Vols.). BLAKE (each) | 6s. 0d. |
| Pot Plant Culture. DAVIDSON | 2s. 6d. |
| Protection of Buildings Against Vermin. BLAKE | 2s. 0d. |
| Radio and High Frequency Currents. LARNER | 2s 6d. |
| Railway Points and Crossings. DOBSON | 6s 0d. |
| Roof Carpentry. COLLINGS | 2s. 6d. |
| Sheet Metal Work. HORNER | 6s. 0d. |
| Slide Rule. HOARE | 4s. 0d. |
| Steel Square and Roofing. DRAPER | 2s. 6d. |
| Superficial Measurement. HAWKINS | 4s. 0d. |
| Surveying. BAKER and LESTON | 3s. 6d. |
| Upholstery and Cutting Out. BITMEAD | 2s. 6d. |
| Valuation Tables. M'CAW | 5s. 0d. |
| Vegetable Culture. DAVIDSON | 2s. 6d. |
| Veterinary Aid. ARCHER | 7s. 6d. |
| Watch Repairing and Cleaning. GARRARD | 6s. 0d. |
| Wireless Telephones. ERSKINE-MURRAY | 4s. 6d. |
| Woodcarving for Amateurs. A LADY | 2s. 6d. |
| Woodworker's Handybook. HASLUCK | 2s. 6d. |
| Woodworking Machinery. BALL | 3s. 6d. |

¶ *Additional volumes in this Series are constantly being published. Latest list will be sent on application.*

LONDON: CROSBY LOCKWOOD & SON

PRINTED IN GREAT BRITAIN BY
WILLIAM CLOWES AND SONS, LIMITED, LONDON AND BECCLES.

# PREFACE

Among the rank and file of the electricity supply industry there may be observed a tendency to regard the rotary converter as a rather mysterious machine, of not quite the same order as the c.c. or a.c. generator. This attitude is encouraged by a statement such as "rotary converters embrace theoretical principles quite different from, and perhaps more difficult to comprehend than, those applying to simple alternators and dynamos," which has been made by one author.

The present writer ventures to assert that, on the contrary, it is only by means of a thorough grasp of the principles of operation of the c.c. generator and its near relative, the alternator with a lap winding, that the rotary converter can be understood. In the book now placed before the reader the subject is considered first of all as c.c. machine, then as alternator, and finally as rotary converter.

In order to give the book as wide an appeal as possible the treatment throughout is non-mathematical. By adopting this form it is hoped to be of assistance to men of all grades who have to do with the running of rotary converters, and who desire a closer acquaintance with the principles involved in their operation. In working on these lines, much of what is given is in the form of direct statement, without any proof of correctness being given;

this was unavoidable within the limits of treatment laid down. No particulars have been given of the construction of the machines or accessories, such as switch-gear, etc., excepting where such information is essential to a proper understanding of the working of these.

In dealing with the operations of starting and paralleling, the aim has been to display as clearly as possible the principles on which the different methods depend, rather than to describe the practice employed by this, that, or the other maker, and the diagrams used in this section have been specially prepared with that end in view. Complete diagrams of connections, while no doubt very imposing in appearance, are of little use, and are seldom worth the trouble of tracing out in detail. Moreover, they seem to have a knack of always differing in some respect from the installation one is particularly interested in, even when ostensibly representing a similar lay-out. The keen student will derive more benefit from tracing out his own job and making his own diagrams; in the process acquiring an intimacy with it which is impossible from the study of the same diagram ready made.

The information given on failure to synchronise and reversal of polarity may be considered in some quarters as unnecessary, yet it can be very useful at times. The operations described for correcting these irregularities have all been taken from actual practice, but should, nevertheless, not be attempted unless the principle underlying them is thoroughly understood. Anything in the nature of merely learning the motions by rote from the book is strongly to be deprecated. In this connection also, it is realised that the scope allowed for the exercise of initiative in these matters, on the part of operators and attendants, varies widely in different undertakings.

The last chapter in the book deals with the motor

converter, a machine which in some points resembling, yet in others differing from, the rotary converter, is perhaps less easily understood. In this chapter it has been found convenient to demonstrate certain relationships by simple mathematical statements: in each case, however, care has been taken to state the line of reasoning and the conclusion arrived at in ordinary language also, thus preserving the character of the treatment throughout.

In conclusion, it is hoped that this book will help readers to know the rotary and motor converters as they really are, not a mystery, but very interesting pieces of apparatus capable of being understood, so far as their operation is concerned, by all who have to do with them. If this object is attained, the result will be an added interest, and increased efficiency, in the performance of duties which tend, by constant repetition, to become monotonous and perfunctory.

The thanks of the author are due to Messrs. Mather & Platt, Ltd., for their courtesy in response to a request for information regarding their patent self-synchronising system.

E. F. S.

# CONTENTS

## CHAPTER I

### THE DYNAMO-ELECTRIC MACHINE



## CHAPTER II

### THE CONTINUOUS CURRENT GENERATOR



## CHAPTER III

### THE CONTINUOUS CURRENT MOTOR



## CHAPTER IV

### THE ALTERNATING CURRENT GENERATOR AND MOTOR

## CHAPTER V

VECTOR DIAGRAMS—INDUCTANCE AND CAPACITANCE



## CHAPTER VI

POLYPHASE MACHINES



## CHAPTER VII

ALTERNATORS IN PARALLEL



## CHAPTER VIII

THE ROTARY CONVERTER

## CHAPTER IX

### PRESSURE CONTROL



## CHAPTER X

### METHODS OF STARTING



## CHAPTER XI

### METHODS OF STARTING (*continued*)



## CHAPTER XII

### METHODS OF STARTING (*continued*)

## CHAPTER XIII

### PARALLEL AND INVERTED RUNNING—3-WIRE BALANCING



## CHAPTER XIV

### TRANSFORMER CONNECTIONS



## CHAPTER XV

### THE MOTOR CONVERTER

# ROTARY AND MOTOR CONVERTERS

## CHAPTER I

### *THE DYNAMO-ELECTRIC MACHINE*

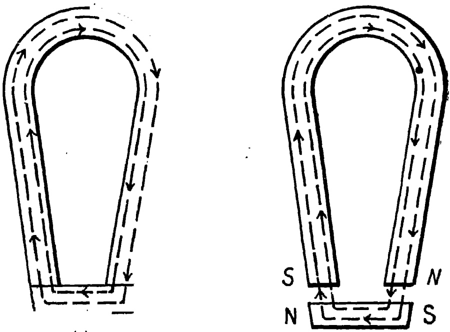
**The Three Essentials.**—The rotary converter belongs to the class of dynamo-electric machines, which also includes the continuous current generator and motor, and the alternating current generator and motor. The dynamo-electric machine has been defined as one in which, by the agency of electro-magnetic induction, mechanical energy of rotation is transformed into electrical energy, or vice versa. In such machines there are three essentials upon which the whole principle of operation is based. These are (1) the magnetic flux, (2) the active conductors, and (3) a relative movement between the two first in a particular manner, when in accordance with the laws of electro-magnetic induction, an electro-motive-force is induced in the conductors.

The magnetic flux is produced by the field magnets, and passing through the armature which carries the conductors, the movement of the one relatively to the other is furnished by the rotation of either the magnets or the armature, the other member being stationary. In the rotary converter

the field magnets are invariably fixed and the armature rotates.

**Magnetism.**—It is first of all important to realise that magnetism always exists in a complete circuit, so that a flux, if followed out along its line of action, must bring the observer back to his starting point.

The familiar toy horse-shoe magnet, Fig. 1 (*a*), affords a simple example from which to approach the large types




(*a*) Fig. 1. (*b*)

of magnet used in electrical machines. The magnet, of steel, is considered as being traversed by a flow, or flux, of magnetism in a certain direction throughout its length, which has the effect of holding the small keeper, or armature close against the two ends of the magnet, these latter being called the poles; the flux traversing the whole combination, magnet and armature, as indicated by the broken lines in the figure.

If the armature is pulled away from the poles against the attracting force and held at a little distance, the flux exists in the airgaps between it and the poles, the circuit then comprising the magnet, the two airgaps, and the armature, as in Fig. 1 (*b*). The reason for this is that up to a certain distance away from the poles, the armature plus the two airgaps offers a path of less difficulty, or lower reluctance as it is called, for the flux than that direct across through the air from pole to pole, although a small flux will travel by the latter route.

As the distance of the armature from the poles is increased the flux traversing it becomes less, more and more crossing direct from pole to pole.

The flux is considered as having a definite direction, so that where it crosses an airgap it may be said to leave one pole of the magnet and enter the other.

This agrees with the two poles having different characteristics and for distinction they are named north and south, the former being a pole which has the flux coming out of it, and the latter one with the flux entering it.

The two poles are therefore said to be of opposite polarity or sign.

When the armature is near the poles as above described a large part of the flux traverses it, with the result that it also becomes a magnet having two opposite poles.

A little consideration will show that as the flux at each airgap is leaving one pole of the horse-shoe and entering one pole of the armature or vice versa, the two poles adjacent to each other will be of opposite sign, shown by the lettering N and S in Fig. 1 (*b*).

In accordance with the law that "like poles repel and unlike poles attract," there will then be a force between the two tending to close the airgap, and if this force is strong

enough, whichever is free to move will do so until they are in contact and the flux has an all steel path.

The flux is assumed to consist of lines of force travelling in the given direction, so that the airgap may be considered as being crossed by a number of lines of force leaving or entering the poles.

A region or space traversed by lines of force is known as a magnetic field, and the strength or density of the field is measured in lines per square inch or square centimetre, a field of unit strength being one which will produce a certain effect which is capable of being measured by the force it exerts.

The horse-shoe magnet just considered is of the type known as a permanent magnet. That is, it has received its magnetism from some other source and by virtue of an inherent property of steel it has retained some when the magnetising agent was removed, this giving it its name.

Except for very small machines, however, permanent magnets could not be made strong enough, so that other means are employed whereby fluxes can be obtained of the densities required.

**Electro-Magnets.**—It is found that a wire carrying a current is surrounded by magnetic lines of force in such a manner that, to an observer looking along the wire in the same direction as the current is flowing, the flux acts in a clockwise direction around it.

If the wire is formed into a coil of one turn the flux will pass through the loop thus made, and the conductor and flux will be linked one with the other, the total number of such linkages depending on the strength of the current.

In a coil of two turns side by side the flux due to each turn links with both, so that the total flux through the coil is twice that with one turn for the same current.

Increasing the number of turns increases the number of

linkages in proportion, the whole of the flux due to all the turns passing through the coil and returning along the outside to complete the magnetic circuit.

The force producing a magnetic flux is called a magneto-motive-force or m.m.f., which term is analogous to electro-motive-force or e.m.f. in an electrical circuit.

The m.m.f. is proportional to the ampere-turns of the coil, that is, the product of the current in amperes and the number of turns in the coil, so that by varying either of these the m.m.f. may be varied.

If the coil has no solid core, or has a core of some non-magnetic material, the flux will be proportional to the m.m.f. and will always be the same for a given value of the latter, whatever be the material of the core.

With iron or steel cores, however, this does not hold good, as in the first place greater fluxes will be produced with a given m.m.f. than with non-magnetic cores, while with different qualities of these two metals the flux densities will also vary. Further, as the density in an iron or steel core increases, a state is reached when an increase of m.m.f. brings about a comparatively small change in the flux, the core then being said to be saturated.

The stronger flux produced in iron or steel is due to the greater permeability possessed by these metals, this term referring to the readiness with which any substance permits of the passage of the flux, and being therefore the opposite to reluctance.

By the inclusion in any part of a magnetic circuit of an iron or steel path, the reluctance of the whole circuit is reduced and the whole flux increased.

Practically all other substances are non-magnetic, that is, their permeability is the same as that of air, and a magnetic flux is not affected by their presence.

Magnets deriving their m.m.f. from the current in an

encircling coil are called electro-magnets, and have the advantage that the flux density may be controlled by varying the exciting current.

When the direction of the current in the coil is known, the direction of the flux can be deduced from the statement above referring to a single wire. If an electro-magnet is viewed from the side with its axis horizontal, so that the current is passing upwards in the side of the coil nearest the observer, the flux will be clockwise round the wires at the top, and anti-clockwise round those at the bottom of the coil, and therefore from right to left in the core; the north pole will be on the observer's left hand.

By placing the right hand palm downwards on the coil with the fingers parallel to the turns and pointing in the direction in which the current is flowing, the thumb, held out at right angles to the fingers and across the turns parallel with the core, will indicate the direction of the flux; will point to the north pole. Also, if the coil is viewed from one end, the south pole will be towards the observer if the current is flowing round the coil in a clockwise direction, and the north pole towards him if the current is anti-clockwise.

All these relations may be checked by means of the diagrams of a horse-shoe shaped electro-magnet in Fig. 2.

Electro-magnets are used in all dynamo-electric machines, those having permanent magnets being known as magneto-electric.

**Multipolar Magnets.**—Field magnets for rotary converters usually have more than two poles, and are then termed multipolar. They take the form of a ring having inwardly projecting arms, the former being known as the yoke and the latter the pole-pieces or poles. There must be an even number of poles, and the exciting coils, which

are mounted on the pole-pieces, are so connected as to give adjacent poles opposite signs.

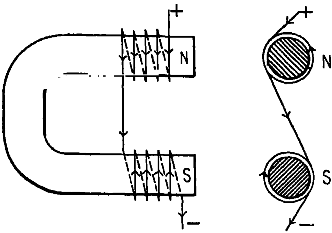



Fig. 2.

Fig. 3 represents a field magnet having four poles, the

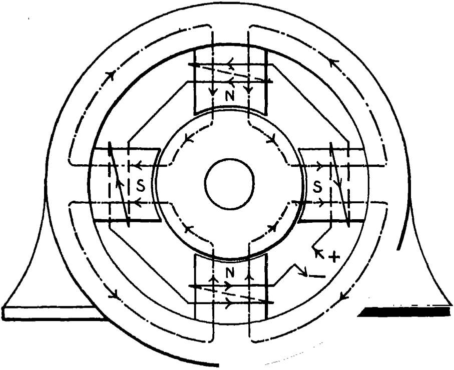



Fig. 3.

exciting circuit being indicated, and the paths of the fluxes shown by the broken lines. In the space between the poles is the armature, which is cylindrical and carries the flux from pole to pole. It will be seen that the flux in any pole divides into two parts, each flowing in opposite directions, both in the yoke and in the armature.

The airgaps between poles and armature are made very small on account of their high reluctance, and to prevent leakage of the flux from one pole to the next without entering the armature. The result is that the flux passes across the airgap and lies practically at right angles to the motion of the surface of the armature under the poles.

**The Active Conductors.**—The second essential to the operation of the machine, the active conductors, are arranged in slots formed lengthwise in the armature surface, being insulated from the core and from each other. In this position, when the armature rotates they are carried round with it and are thereby caused to pass through the flux.

**The Motion.**—This movement of the conductors through the flux constitutes the third vital element in the machine, and it is particularly to be observed that the movement takes place in a direction at right angles to the length of the conductor, and also at right angles to the flux. That is, the conductor moves sidewise and not endwise; cutting across the flux, not moving parallel to it.

**Electro-Magnetic Induction.**—By the law of electro-magnetic induction, when a conductor is caused to move in a magnetic field in such a way that it cuts across the flux, an electro-motive-force is induced therein.

A definite relationship exists between the direction of the flux, direction of motion of the conductor, and direction of the induced e.m.f., and this may conveniently be indicated by Dr. Fleming's right-hand rule, in which the fore-

finger, thumb, and centre finger of the right hand are used to denote flux, motion, and e.m.f.

If the hand is held with these members extended at right angles to each other, that is, the fore-finger in line with the hand as in pointing, the centre finger out at right angles to the palm, and the thumb extended sideways from the palm, the directions in which these are pointing will give the indications required.

For example, at a north pole, the hand is held with the fore-finger pointing towards the armature and the thumb in the direction in which the armature moves at that place, when the centre finger held in the proper manner will lie parallel with the armature conductors, and as stated above will indicate the direction of the induced e.m.f. in the conductors under that pole.

The reader is urged to familiarise himself with the right-hand rule, observing that with the same direction of rotation, reversing the flux reverses the e.m.f. induced. Similarly with the direction of flux unchanged, reversing the motion also reverses the e.m.f.

In view of the assumption that current flows in the direction of the e.m.f. the centre finger may also represent the current, the memory being assisted by associating the initial letters of fore-finger and flux, and centre finger and current, while the word thumb, when spoken, runs naturally into its associated term, motion.

The value of the e.m.f. induced in a conductor depends on the rate at which it cuts the flux, that is, the number of lines of force cut in a given time.

This rate of cutting will depend on three things, namely, the flux density, the active length of conductor, and the speed of the conductor.

If two or more conductors are joined in series so that their e.m.fs. act in the same direction, this is equivalent

to increasing the active length, and the e.m.f. available will be increased in proportion.

In practice, the total active length of conductor is fixed by the design of the machine, and cannot be varied when this is in operation.

Likewise, the speed of the conductors is usually fixed by the necessity for running the engine, or other driving agent, at that speed at which it is designed to develop its rated power.

The flux density, however, is readily controlled by altering the value of the exciting current, and this is the means invariably employed to control the e.m.f. generated by machines in commercial service.

It will be evident that as the conductors pass under successive poles, these being of opposite sign there will be reversals of the e.m.f. induced.

Leaving out of consideration, for the moment, the connections between the conductors and viewing only their active parts, *i.e.* those parts embedded in the armature slots and therefore cutting the flux, it will also be evident that when the armature is revolving there will be, at every instant, a group of conductors under each pole.

The conductors of any one group will have their e.m.fs. in the same direction, while the e.m.fs. in conductors in adjacent groups will be in opposite directions.

The groups themselves will be stationary, while the individual conductors forming them will pass from one group to the next and so on, their e.m.fs. alternating in direction as they do so.

This is shown in Fig. 4, which represents the armature and field poles of a four-pole machine.

The small circles on the armature represent the conductors in cross-section, while the crosses and dots in them show the direction of the induced e.m.fs., the cross indi-

cating the tail and the dot the point of an arrow flying away from or towards the reader.

The blank circles represent conductors in those parts of the field midway between the poles, in which no e.m.f. is induced owing to their motion being parallel to the flux. These positions are known as the neutral points of the field.

As the conductors are distributed symmetrically round

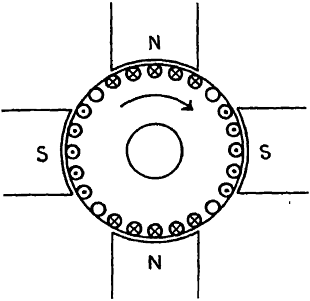



Fig. 4.

the armature it follows that the diagram may be taken to represent the armature and conductors at practically any instant while they are revolving.

The groups of conductors having opposite e.m.fs. will be observed, and it is hoped that there will be no difficulty in grasping the idea of stationary groups of moving conductors.

**Field Excitation.**—Before passing on to the consideration of the means employed to utilise the e.m.fs. induced

in the conductors, the question of the source of excitation for the field magnets may be disposed of.

As most dynamo-electric machines are self-excited, that is, they have their field magnets excited by current generated by the machine itself, it becomes necessary that the magnets should possess some permanent magnetism when the exciting current is absent.

Were the magnets dead under these conditions, there would be no flux to start the exciting current and nothing could be done with the machine until a flux was provided.

Fortunately, as remarked earlier, steel has the property, when once magnetised, of retaining some of the flux after the exciting agent is removed, and for this reason field magnets are made of steel.

This remaining flux, called the residual flux, is sufficient to induce a small e.m.f. in the conductors when the machine is started, and this sends a current through the exciting coils which builds up the flux to its full value as the e.m.f. increases. Thus the machine is entirely self-exciting.

Field coils are usually joined in series with each other, and connected to the main terminals of the machine, a variable resistance or regulator being included in the circuit to allow of the excitation being varied at will.

When connected in this way the machine is termed shunt wound, the field circuit being in shunt or parallel with the load.

In another method the coils are connected in series with the main circuit of the machine, so as to carry the load current. This is known as series excitation, and on account of the larger current the field coils are of fewer turns of heavier gauge than with shunt excitation.

In the shunt-wound machine the e.m.f. available at the

main terminals falls off as the load increases, owing to increased pressure losses with the heavier current.

This tendency may be removed by providing a few turns of series field winding so that the excitation varies with the load, the machine then being said to be compounded.

When over-compounded, the series turns are sufficient to cause the terminal pressure to rise with increasing load, this being desirable in certain circumstances.

Rotary converters are either shunt or compounded, as required by the conditions under which they are to work, this point being more fully dealt with when the subject of pressure control is reached.

## CHAPTER II

### *THE CONTINUOUS CURRENT GENERATOR*

**The Lap-connected Winding.**—In the last chapter it was seen that e.m.fs. are induced in the armature conductors as they pass under the poles of the field. The means of making these e.m.fs. available at the terminals of the machine has now to be considered. By connecting two or more of the conductors together in series their e.m.fs. may be added, and the winding takes its name from the manner in which this is done.

The type of winding invariably used in the rotary converter is the lap winding, in which the conductors are connected so as to form a number of coils overlapping one another and so advancing progressively round the armature. Each coil consists of one turn, or two conductors with their end connections, and in order that the e.m.fs. shall be in the same direction round the coil, the conductors must be spaced so that the distance between them is approximately equal to that between two poles of opposite sign, or one pole pitch. The whole forms a closed winding, symmetrically distributed round the armature core, so that by starting at any point, it may be traced out until all the conductors have been traversed and the starting point regained.

Such a winding would be very difficult to represent in a diagram, owing to its cylindrical shape. The plan has

been adopted, therefore, in Fig. 5, of showing only a part of the winding as if it were laid out flat; sufficient being taken to embrace three of the field poles, these being indicated by the heavy broken-line rectangles, and their polarity by the letters N and S. No reference is made to the total number of poles in the field, this being immaterial, as will be understood from the following.

It is a characteristic of the lap winding that there are as many separate parallel paths from negative to positive brushes as there are poles in the field, the conductors in any one of these paths being under the influence of a pair of adjacent poles. By taking three consecutive poles and a corresponding part of the armature winding for consideration, we may study what is going on between one set of brushes on the commutator and its immediate neighbours on either side, or in two of the paths through the winding.

Bearing in mind that both the field system and the armature winding are symmetrically arranged, it will be clear that the diagram may represent any three poles of the given signs out of a field system of any number of pairs of poles, and also any equal number of armature conductors from any part of the corresponding winding.

Furthermore, the same diagram may be taken to represent the winding at practically any instant during the rotation of the armature.

It will be understood that the number of conductors in the winding shown in the diagram has purposely been made small, as it would be impossible to show in a small diagram the large numbers used in actual practice. This, of course, in no way affects the principle involved.

The diagonal lines at the top and bottom of the figure represent the end connections, and the straight lines between them the active conductors. Actually, the conductors do not lie singly in the slots, several being grouped

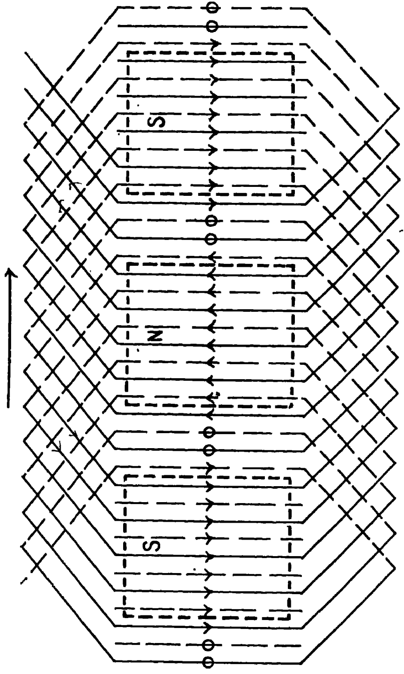



Fig. 5.

together in each slot. Further, the conductors are arranged in two layers, the end connections running opposite ways from the conductors in each layer. Thus if the left-hand conductor of a coil is at the top of its slot, the right-hand one will be at the bottom of its slot, and by this means the end connections are kept clear of each other. The upper layer of conductors and connections in Fig. 5 is shown by full lines, and the lower layer by broken lines.

It will be observed that so far no reference is made to a commutator, neither is one shown in Fig. 5, as it is desired to emphasise the fact that the winding is complete without the commutator, which is simply a means for making connection between the armature winding and the external circuit in a particular manner.

Considering the field poles in Fig. 5 as being above the page and pointing downwards, and the motion in the direction indicated by the arrow above the figure, the right-hand rule will show that the e.m.fs. induced in the conductors will be in the directions shown by the arrow-heads thereon. Tracing the winding out from the conductors in the neutral zones of the field, marked O, it will be found that those next connected to them on either side have their e.m.fs. in opposite directions, and that of a group of conductors in series between one neutral zone and the next, all have their e.m.fs. in the same direction, and therefore cumulative.

The number of neutral points in the winding will equal the number of poles, and the latter being an even number (any number of pairs of poles) the number of series groups of e.m.fs. induced in the winding will also be even. As the e.m.fs. in successive groups are in opposite directions, there will be an equal number of e.m.fs. in each direction, so that the sum of the e.m.fs. acting round the winding is zero.

The steps gone through in reaching this point may be repeated briefly.

When the armature is rotating, all conductors under poles of similar sign have, at any instant, their e.m.fs. in the same direction, those under poles of opposite signs having e.m.fs. in opposite directions.

By the lap method of connection, conductors situated a pole pitch apart are joined to form one turn of the winding. successive turns being again joined in series so as to form a continuous winding.

When the armature rotates the magnetic field divides the winding into sections having alternately opposing e.m.fs. the numbers of opposing sections being equal, and the sum of the e.m.fs. round the winding therefore zero.

The magnetic field being stationary the distribution of e.m.fs. in the winding is also stationary, the individual conductors passing from one section to another at the neutral points of the field, and the total number in each section remaining constant.

This may be shown diagrammatically by drawing a circle to represent the closed armature winding with all its conductors in series, as in Fig. 6 for a four-pole machine. The neutral points $a$, $b$, $c$, and $d$, are shown dividing the conductors into four active groups, the arrowheads in each of the latter indicating the direction of the induced e.m.f. therein.

Between any two adjacent neutral points there will be the full pressure due to the added e.m.fs. of the conductors between them in series.

On the other hand, between alternate neutral points as $a$ and $c$, or $d$ and $b$, there are two sections of the winding having opposing e.m.fs. so that the pressure between these points is zero.

It will be necessary, then, in order to get the full pressure

generated by the machine, to connect the external circuit to the winding at those neutral points situated one pole pitch apart.

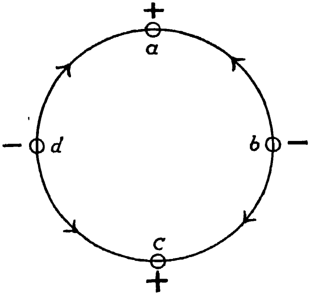



Fig. 6.

As all the conductors, in turn, occupy the neutral points, the connection has to be made by providing stationary brushes rubbing on contact surfaces connected to the conductors.

**The Commutator.**—The commutator is simply a succession of extended contact surfaces arranged in the form of a cylinder and revolving with the winding, so that stationary brushes bearing thereon maintain a constant connection between the moving winding and the stationary external circuit.

It will be seen in Fig. 6 that the neutral points *a* and *c* have the e.m.fs. in the adjacent sections of the winding acting towards them, while at *b* and *d* the e.m.fs. are acting away from the neutral points. The former will be positive and the latter negative, as the current which flows in the

direction of the pressure is assumed to leave the generator by the positive brushes and return to it by the negative.

The brushes resting on the commutator at bars connected to conductors in neutral points *a* and *c* will therefore be positive, and may be connected together as there is no difference of pressure between them. Brushes making contact with points *b* and *d* will be negative and may also be connected together, the common connections of each set of brushes being taken to the main terminals of the machine.

By tracing out the paths through the winding it will be found that there are as many between brushes of opposite sign as there are poles in the field, in this case four, and in parallel with each other.

When the machine is on load the current will divide equally between the various paths, and each set of brushes will carry only a portion of the current, according to the number of poles in the field.

The connection between the commutator bars and the winding is made as shown in Fig. 7, which is identical with Fig. 5 except for the addition of the commutator bars at the bottom, the brushes being shown by the shaded rectangles + and −, positive and negative respectively.

There are two conductors connected to each bar and the winding takes one turn between each pair of adjacent bars, so that the difference of pressure between the latter is that due to two conductors.

Owing to the connections to the commutator being made in the middle of the front end connectors, the brushes are not placed opposite the neutral points of the field, but opposite the centre of the pole pieces, the neutral points of the commutator being staggered half a pole pitch from those of the field.

**Load Torque.**—The distribution of the current in the

winding when the machine is on load is shown by the arrow-heads in Fig. 7, and is the same as that shown in Fig. 5 for the e.m.fs.

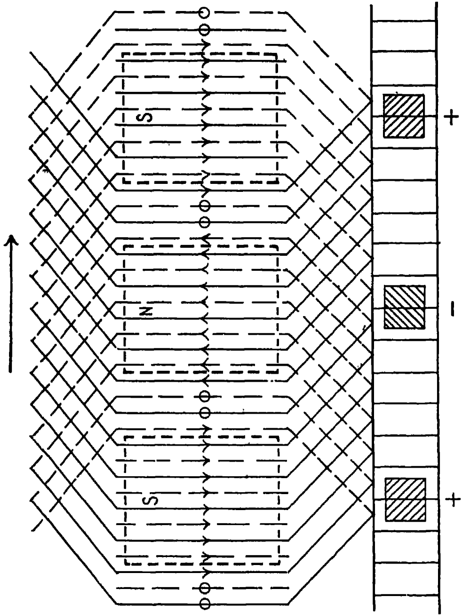



Fig. 7.

Now when a conductor carrying a current is placed at

right angles to a magnetic field, it is acted on by a force tending to move it in a direction at right angles to its own length and to the flux.

This is so whether the current is that due to the e.m.f. induced by its own movement or not.

The direction of the force is found by Fleming's left-hand rule, in which the fore and centre fingers stand for flux and current as in the right-hand rule, while the thumb shows the direction in which the conductor is urged to move.

Applying this rule to Fig. 7 it will be seen that the effect of this force is to oppose the rotation of the conductors, thereby imposing what is known as a load torque on the armature which has to be overcome by power from the engine which is driving it, all the time the machine is acting as a generator.

The load torque is proportional both to the current and the flux, so that an increase in the load by increasing the armature current produces a larger torque, more power being therefore required to maintain the rotation.

The relationship between flux, motion, e.m.f., current and torque, can be illustrated very simply by holding out both hands together, as in the right- and left-hand rules.

Both fore-fingers being made to point in the same direction, as representing the same flux, and both centre fingers in the same direction at right angles to the former, that on the right hand will indicate the e.m.f. induced, and that on the left hand the direction of the current.

The thumbs will now be found to be pointing in opposite directions, the right hand showing the motion producing the e.m.f. and current, and the left thumb the force acting on the conductors as a result of the current.

**Commutation.**—If the conductors in the neutral positions in Fig. 7 are traced out it will be found that they form

turns of the winding which are short-circuited by the brushes, these bridging the two commutator bars between which such conductors are connected.

In this position the current in the coils is said to be undergoing commutation, the process of which is as follows.

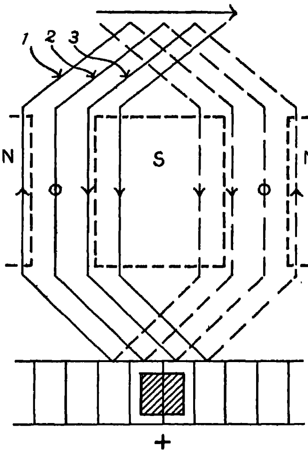



Fig. 8.

Fig. 8 may be taken as representing either three neighbouring coils at a particular instant of time, or a single coil at three successive instants during its passage through the neutral zone.

Up to the moment of arriving at the position marked 1

the coil is carrying the full current of that section of the winding of which it forms a part, in a clockwise direction on its way to the brush, which is therefore marked +. Between positions 1 and 2 the brush bridges the gap between the two bars of this coil and the current has a direct path from the coil behind to the brush; the current in the short-circuited coil therefore falls to zero.

When the leading bar of this coil passes out from under the brush into position 3 it then forms part of the next active section of the winding and has to carry the full current once more, but this time in the opposite direction, or anti-clockwise round the coil.

If it were possible for the current to stop and start instantaneously, no difficulty would arise over commutation, the current ceasing from one direction and re-starting in the other as the coils were cut out of and into the active sections of the winding.

Actually, however, it is not possible for the current to change its value in this manner, on account of the effect of self-induction, which is a property possessed to a greater or lesser degree by every current-carrying conductor.

This property will be more fully dealt with when we come to consider alternating currents, but it will suffice here to say that when there is a change in the value of the current in a conductor, the effect is to induce in the conductor itself an e.m.f. which tends to oppose such change. This is known as the e.m.f. of self-induction or reactance e.m.f., and other things being equal, the greater the current change, or the greater the rate at which the change takes place, the greater will be the reactance e.m.f.

At the first instant of the brush bridging the gap between the two bars of a coil, the contact between the brush and the newly arriving bar is very slight and the resistance of the contact comparatively high.

The current therefore flows partly across this contact and partly round the coil to the leading bar, and so to the brush.

As the bar moves on the area of contact increases and the contact resistance correspondingly decreases, more current passing direct and less round the coil, until the whole of the armature current is passing direct from the second bar to the brush.

The reactance e.m.f., however, delays the fall of the current in the coil, so that it reaches zero later than it would if it were only dependent on the varying contact between the brush and the second bar.

Similarly, when the leading bar is about to leave the brush, the contact resistance gradually increases, so diverting more of the current round the coil until the bar leaves the brush, when the coil has to carry the whole of the current.

Here, now, the reactance e.m.f. opposes the rise of the current with the result that when the bar leaves the brush the current has not reached the full value in the coil and has therefore rapidly to change its value. This causes an increase in the reactance e.m.f. and may result in the current from the bar to the brush persisting after the two have separated, so giving rise to sparking.

To prevent this sparking, with its injurious effects on the commutator, it is necessary to use some means of assisting the reversal of the current.

The method in general use consists of bringing the coils under the influence of a reversing flux during the time they are short-circuited by the brushes.

At one time this was done by shifting the brushes forward in the direction of rotation of the armature, so that the coils, when short-circuited, were in the field of the next pole ahead, instead of being in the neutral zone. By

this means an e.m.f. was induced in the coils in a direction opposite to the current at the moment of short-circuiting, thereby assisting the reversal and counteracting the effect of the reactance e.m.f.

Several disadvantages attached to this method, the chief being that as the load increased the brushes required advancing still further, while on the load decreasing they had to be brought back.

This was due partly to the greater current at heavier loads requiring a stronger reversing-flux, and partly to the fact of the increased armature current producing a reaction distorting the main flux in the direction of rotation.

Furthermore, the shifting forward of the brushes introduced an additional armature reaction whereby the flux was weakened by increased armature current.

For these reasons the method of giving "lead" to the brushes to obtain sparkless commutation was very unsatisfactory, especially for machines dealing with varying loads, so that with modern machines a reversing-flux is provided by commutating poles. These, also called auxiliary, or interpoles, are fitted to the main field magnet frame midway between each pair of main poles.

They are fitted with exciting coils which carry the whole or a part of the load current of the machine so that the strength of the reversing-flux varies with the load, and consequently with the current to be reversed in the armature coils.

A little consideration will show the polarity required at the interpoles in relation to the main poles.

Previously to arriving at the commutating zone the coil has been carrying a current in a direction corresponding to the e.m.f. induced by the flux it has just passed through. While in the neutral zone this current has to fall away to zero and then build up in the reverse direction, or that

corresponding to the e.m.f. induced by the next poles ahead.

The commutating poles, therefore, must be of the same sign as the next poles in the direction of rotation, and accordingly an e.m.f. is induced in the coils under them which hastens the fall of the former current to zero ; the coil being short-circuited by the brush a current starts in the new direction, which, with correct design, will reach the value of the armature load current by the time the leading bar of the coil leaves the brush.

By the use of interpoles the brushes may be kept in a fixed position for all loads, and modern rotary converters are invariably provided with them.

Although, in the diagrams used here, the brushes are shown as only wide enough to cover two commutator bars, in actual practice they usually cover at least three and sometimes four bars. This increases the short-circuiting period, so allowing more time for the process of current reversal.

**Armature Reactions.**—When carrying current, the armature of a c.c. generator becomes, in effect, an electromagnet having the same number of poles as the field system of the machine.

It has already been noted that all the conductors under any one pole of the field form a group having their currents in the same direction. Each of these groups will be encircled by a flux due to the current therein, and these fluxes will be in alternate directions in the core, that is, towards and away from successive neutral points.

Referring to Fig. 9, which is a cross-section of the winding and field magnets of Fig. 7, with the addition of inter-poles, and bearing in mind the direction of the flux encircling a current-carrying conductor, the derivation of the heavy

broken lines, representing the fluxes due to the armature currents, will be readily understood.

The armature poles are located at the points where the flux enters or leaves the core, these coinciding with the neutral zones of the main field: the armature poles are therefore displaced from the field poles by one half a pole pitch, and their sign is the same as that of the next field pole ahead.

In completing its circuit the armature flux crosses the air-gap and travels across the field pole, so that where it enters or leaves the pole it either reduces or increases the main flux, according to the sign of the latter.

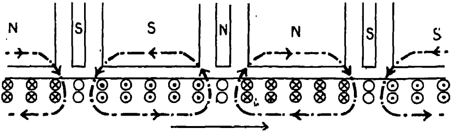



*Fig. 9.*

The total result is that at each pole the flux is reduced at the leading tip and increased at the trailing tip, so producing a displacement or distortion of the main flux in the direction of the rotation of the armature.

The armature flux producing this distortion is known as the cross flux, and varies with the armature current and therefore with the load on the machine.

The effect of the cross flux was briefly referred to in connection with the practice of giving lead to the brushes to prevent sparking. The other armature reaction mentioned at the same time will be explained here, although it does not arise in machines where the brushes are kept in the exact neutral point midway between the poles.

We have seen that the armature flux has its poles coinciding with the neutral points of the winding, these latter being the points on either side of which the current is in opposite directions.

Now the distribution of the current in the winding depends on the position of the brushes. When these are in the neutral zones of the field, the current distribution corresponds to the distribution of the e.m.fs. induced in the conductors, the latter being fixed by the flux.

If the brushes are moved forward, however, the coils which are in the neutral zones of the field are thrown into circuit, while those which are short-circuited by the brushes are in the flux of the next poles ahead, this flux then being used to assist the current reversal.

The neutral points of the current distribution no longer coincide with those of the e.m.f. and as the armature flux arises from the current, the armature poles are shifted forward and therefore approach more nearly the poles ahead.

Instead of the distortion being uniform as before, the leading pole tips will be weakened more than the trailing ones are strengthened, and the total flux will be reduced accordingly, as well as distorted.

If it were possible, leaving out other considerations, to move the brushes forward through one-half a pole pitch, the centres of the armature poles and field poles would coincide, and there would be weakening but no distortion.

The armature flux may be divided into two parts, the cross flux and the back flux, these having differing relative values depending on the position of the brushes.

With the brushes in the neutral zones of the field the back flux is zero and the effect wholly distortion, while with a forward shift of half a pole pitch the cross flux is zero and the effect weakening only.

For intermediate positions there is a combination of distortion and weakening.

From the foregoing it will readily be seen that if the brushes are moved backwards or given lag, the armature poles are brought nearer to the field poles behind, or to poles of unlike sign, the effect then of the reaction being to strengthen the main flux in addition to the distortion.

When examining Fig. 9 it might be thought that the commutating poles would neutralise the cross flux, as the two fluxes are in opposition in the neutral zone. This is not so, however, owing to the magnetic path provided by the adjacent main pole pieces.

If the interpoles were left unexcited a part of the cross flux would pass through them, completing its circuit through the yoke and adjacent interpoles. Sufficient m.m.f. has therefore to be provided by the interpole coils to balance the effect of the armature cross flux in the interpole circuit.

With this alone, however, there would still be no reversing flux under the interpoles, so that to furnish this additional m.m.f. is required.

The total result is that the cross flux is neutralised under the interpoles and the commutating flux (which is of opposite sign) established in its stead, the cross flux being diverted to the main pole pieces.

The ampere turns of the interpoles have therefore to be greater on account of the cross flux than they would be if the latter did not exist, but nevertheless the interpoles do not prevent distortion of the main field flux.

The cross flux may be neutralised and distortion prevented by fitting a compensating winding consisting of conductors embedded in slots in the pole faces so as to lie parallel to the armature conductors. By connecting these so that the current in them is in the opposite direction

to that in the armature conductors under them, a cross m.m.f. is produced in opposition to that due to the armature.

The compensating winding is arranged in series with the load so that the compensating m.m.f. varies equally with the armature m.m.f. and thus distortion of the main field is prevented.

Compensating windings are often used on modern c.c. generators, but are not used for rotary converters, as owing to the peculiar operating characteristics of the latter the armature cross m.m.f. is practically non-existent.

The reader should not confuse the damper winding usually fitted to the poles of rotary converters with the winding just described, as the damper has a totally different duty to perform, besides being unconnected with any external circuit. This will be dealt with in due course.

**Equalising Rings.**—In Fig. 6 it will be seen that between any two points diametrically opposite, that is, two pole pitches apart, the effective pressure is zero, there being included in the arc of the circle between them equal lengths having arrows in opposite directions.

As long as the e.m.fs. induced in each section of the winding are exactly equal this will hold good.

It sometimes occurs, however, that there are slight differences in the strength of the flux under poles situated in different parts of a multipolar field magnet.

This may be brought about in various ways.

For instance, when the yoke is divided so as to allow of the top half being removed in order to take out the armature when required, the joints, if not carefully fitted, may have sufficient reluctance to cause a sensible reduction of the flux in the circuit containing them as compared with those circuits without.

Or the armature may not be exactly central in the space between the poles, owing to wear of the bearings or other

cause. In these circumstances some of the airgaps will be wider than others, the differences of the reluctances thus varying the flux in the several magnetic circuits.

On account of this the e.m.fs. induced in the different sections of the winding may be slightly unequal.

Owing to the fact that under any one pole there are located parts of two adjacent sections having opposing e.m.fs. there will be no unbalancing of the opposing pressures round the armature, and consequently no circulating current in the winding alone.

When the brushes are placed on the commutator, however, the connections between brushes of like sign will form cross connections to the armature winding, and if unequal pressures are present in the latter, currents will circulate via the brushes and their connections.

When the machine is on load the current will divide unequally between the several paths through the winding, according to the pressures induced therein.

Some sets of brushes will therefore be carrying more current than others, and this in turn will affect the commutation owing to the differing values of the current at separate commutating points.

In order to avoid this, points in the winding at intervals of two pole pitches apart are connected together by conductors of low resistance.

One such conductor, known as an equalising ring or equipotential conductor, will therefore be connected to the winding at one point for each pair of poles in the field.

If each successive coil was connected to its fellows two pole pitches away, the total number of equalising rings would equal the number of coils per pair of poles; but in practice it is usual only to connect about every fourth coil in this fashion. By this means the number of rings is kept down and quite efficient results nevertheless obtained.

Any inequality in the flux under different poles will cause currents to circulate in the equalising rings rather than via the brushes and their connections, and so unequal distribution of the load current between the sets of brushes is prevented.

**Parallel Operation.**—Two or more generators having their terminal pressures equal may be connected together, positive to positive and negative to negative, in parallel.

As their pressures are in opposition when so connected there will be no current in the circuit formed by the two machines; but if an external circuit is connected to the combination a current will flow therein which will divide equally between the armatures of the generators.

One machine may be made to take a larger share of the load by increasing its field, and so raising the terminal pressure, or by lowering the pressure generated by the other.

The way in which generators behave when in parallel depends largely on the way in which their terminal pressures vary with changes in the load, or what is known as the "characteristic" of the machine.

The characteristic of a generator is the name given to a curve which is drawn from observations of the terminal pressures available with varying loads.

If the terminal pressure at no load is the same as at full or other loads, the curve will be a horizontal line; such is a "flat" characteristic.

If the pressure at full load is lower than that at no load the curve will fall towards its full load end, and is then known as a "drooping" characteristic.

On the other hand, a machine which gives a higher terminal pressure at full than at no load is said to possess a "rising" characteristic.

The ordinary shunt-wound c.c. generator has normally a drooping characteristic, on account of the increased

pressure drop due to armature conductor and brush contact resistance with heavier loads.

Compounded machines will have characteristics depending on the amount of compounding for which they are designed; when over-compounded having a rising characteristic.

Machines having drooping characteristics will, in general, run stably in parallel, and the extent to which they will maintain equal division of load depends on the similarity or otherwise of their characteristics.

Those machines in which the pressure drops to a greater degree with increased load will have a tendency to respond less readily to changes in the total load, when in parallel with others having flatter characteristics, on account of the unequal effects of such changes on the terminal pressures of the two classes of machine.

Over-compounded generators, in which the pressure rises with increased load, will not run stably in parallel unless special equalising arrangements are provided.

Without these any difference between the loads carried by separate machines has the effect of increasing the field of the one having the heavier load, so increasing the inequality of the loads, this being the opposite to that which occurs with drooping characteristics.

Furthermore, with compounded machines in parallel, if the pressure generated by one of them were to fall from any cause, such as the slowing down of the engine, there would be a reversal of the current through the armature of this machine. The series field current would also be reversed, reducing the flux and lowering the generated pressure still further, so that the polarity of the field magnets is in danger of becoming reversed.

Equalising is brought about by connecting together the inner ends of the series windings of all the machines, that is, the ends nearest the brushes.

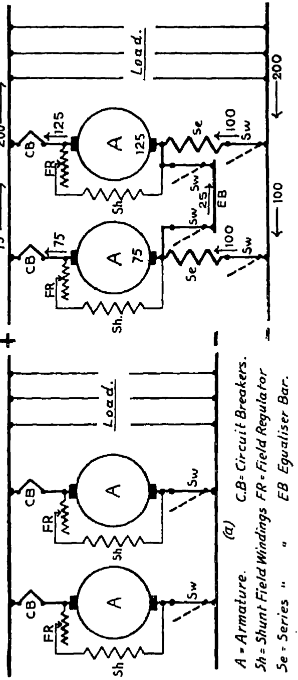

CB
FR
Sh
A
Sw
Load.
(a)
(b)
75
200
125
100
25
Se
EB
A = Armature.
Sh = Shunt Field Windings
Se = Series "
C.B = Circuit Breakers.
FR = Field Regulator
EB Equaliser Bar.

Fig. 10.

By this means they are all placed in parallel between the load and the equaliser, while the armatures are in parallel between the equaliser and the other side of the system.

The connections for machines in parallel are shown in Fig. 10, (*a*) being for shunt-wound and (*b*) for compound.

It will be seen that if the resistances of the series windings are equal, the load will divide equally between them, even if the machines are carrying unequal loads in their armatures by having differing values of shunt field excitation, in which case the difference of the armature currents flows over the equaliser.

Any tendency on the part of one machine to pick up load from the others has no effect on its field; rather the machines are now in the position of having drooping characteristics to such changes, the series winding not being involved; so stability is maintained.

Even if the current is reversed in the armature of one machine there is no change in the series field current, and the polarity is safeguarded from reversal.

The figures against various parts of the circuits in diagram (*b*) represent the current in amperes for a supposed case of unequal loading of the machines, the part played by the equaliser being thereby clearly shown.

The series winding is shown as on the negative side, but it might equally well be on the positive side: obviously, machines to run in parallel must all have their series windings on the same side for equalising.

Sometimes the equaliser connections are brought to switches and an equalising bar on the switchboard, while often the switch is mounted on or close to each machine, and an equaliser cable is run from one to the other.

In all cases the equaliser switch must be closed before, or at the same time as, switching the machine on to the bus-bars, and not opened until after switching off load.

# CHAPTER III

## *THE CONTINUOUS CURRENT MOTOR*

**Motoring Torque and Back E.M.F.**—If we take a shunt-wound c.c. generator which is running in parallel with other generating plant, and gradually reduce the field the armature current will fall to zero.

A further reduction will cause the generated pressure to fall until a current begins to flow in the opposite direction through the armature, and by applying the left-hand rule we see that the conductors are now acted upon by a force urging them onwards in the direction of their former rotation.

It is to be observed that the field current is not reversed, the signs of the terminals remaining unchanged, and the pressure generated in the armature only having fallen to a comparatively small extent below its former value.

The current will depend on the difference between the generated e.m.f., or back e.m.f. as it is now called, and the pressure supplied by the other generators, this being known as the impressed pressure.

By extending the fingers and thumbs of both hands together, as in the right- and left-hand rules, and giving the same direction to flux and motion in each, the relation between the current causing the motion, and the back e.m.f. generated as a result of that motion, may be readily seen.

The engine which we have assumed as driving the machine as a generator previously may now be left out of consideration, the latter acting as a motor receiving electrical energy from the other plant and converting it into mechanical energy of rotation.

If the armature is stationary and an external supply is connected thereto, current will flow in the winding and the armature will rotate, the direction of the motion depending on the relation between the flux and the armature current.

The winding is divided by the commutator brushes into sections, so that all the conductors under poles of the same sign have their currents in the same direction, while in those under poles of different sign the currents are in opposite directions.

All the conductors therefore produce a rotating force in one direction.

A back e.m.f. will be induced in the conductors by their motion through the flux, and the difference between this and the impressed pressure will adjust itself automatically, until it is sufficient to transmit the power required to maintain the rotation of the armature against the various opposing forces, such as friction, windage, etc.

Should this difference be too small, the machine will slow down until the falling of the internal e.m.f. allows a larger current to flow, while if the difference is too great the excessive current causes the speed to rise, increasing the back e.m.f. and thus reducing the power input.

Changes in the load being driven by the motor are met in this fashion, the speed variations of a shunt-wound motor in actual operation being comparatively small between no load and full load.

Variation of the field strength of a motor has the effect of varying the speed; a decrease in the flux, by reducing the back e.m.f., increases the armature current and raises

the speed, while increasing the field strength reduces the speed.

**Commutation.**—In a motor, exactly as in a generator, the conductors have their currents reversed as they pass under the brushes.

There is this difference, however, that in any active part of the winding, the current is in the opposite direction to the induced e.m.f., so that to assist in bringing it to zero and to build it up in the reverse direction, each coil must still be subjected to this opposing e.m.f. after reaching the brush. The interpoles, then, must be of the same sign as the poles behind them, or the reverse of that which obtains in a generator.

These relations are shown in Fig. 11, (*a*) representing the conditions for a generator, and (*b*) those for a similar motor.

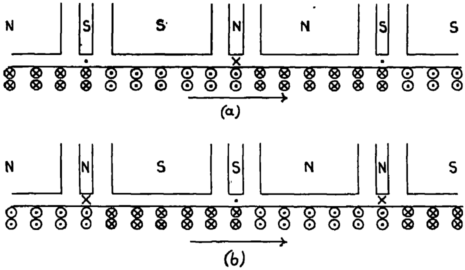



Fig. 11.

The direction of the armature currents is shown, those in (*b*) being in opposition to the induced e.m.f.

In the conductors under the interpoles the direction

of the current on arriving at the point of reversal is shown, while the crosses and dots in the airgap indicate the direction of the reversing e.m.f. induced by the interpole flux.

In a machine which is required to run either as c.c. generator or motor at different times, the interpoles change their signs according to the way the machine is operating, as their exciting coils are connected in series with the armature circuit.

This applies to the rotary converter, which may be used for conversion from a.c. to c.c. or the reverse, and may therefore be considered as generator or motor according to circumstances.

The reader is advised to try all these relationships over by the right- and left-hand rules, in order to get a thorough grasp of the matter.

**Armature Reaction.**—It will also be seen from Fig. 11 that, as compared with a generator, the armature cross flux in a motor will be in the opposite direction relative to the field poles, strengthening the flux at the leading edges and weakening it at the trailing edges. The main flux is therefore distorted in the opposite direction to that of rotation.

**Field Excitation.**—Motors intended for use solely as such may have their field excitation either shunt, series, or compounded, this depending on the service for which they are designed.

Compounded machines intended to run as either motor or generator, should have arrangements to enable the series winding to be reversed or cut out when motoring, to prevent weakening of the field by the reversed current in the armature circuit.

**Starting.**—When a motor is running, the difference between the back e.m.f. and the impressed pressure is

quite small, being just enough to produce the current required for the load, through the low resistance of the armature winding.

With the armature stationary there is, of course, no back e.m.f., so that it is impracticable to apply the full pressure for starting on account of the heavy current which would be produced before the machine could get up sufficient speed to generate a back e.m.f. of the required value.

It is necessary, therefore, to use a special starting device, the object of which is to restrict the current in the motor circuit until the back e.m.f. has built up sufficiently to perform this duty.

This is done by means of suitable resistances, the whole of which are put in series with the armature at first, being afterwards cut out step by step as the speed rises. At each step the current momentarily increases, so speeding up the motor until, the back e.m.f. having attained a higher value, the current falls to a minimum figure, when the next step may be cut out.

When full speed has been reached the whole of the resistance is cut out of circuit and the back e.m.f. then automatically controls the current in the machine, as explained earlier.

It is most important that the pressure should not be applied to the machine unless all the resistance is in circuit, and that the steps should not be cut out too rapidly before the back e.m.f. has had time to rise to compensate for the reduced resistance.

Motor starters are usually equipped with various safety devices to ensure that essential requirements are complied with.

## CHAPTER IV

### *THE ALTERNATING CURRENT GENERATOR AND MOTOR*

**Alternating Pressure.**—An alternating pressure is one which is continually varying from a maximum in one direction to a maximum in the other. Such a pressure is required on the a.c. side of the rotary converter, and is obtained from the same lap-connected winding as produces the continuous pressure at the commutator.

The complete series of changes, known as the cycle, is assumed to start from zero ; the pressure going to maximum in one direction, back to zero, then to maximum in the other direction, and back to zero once more.

In the single-phase machine, such as we are considering at present, two connections are made to the winding at a distance of one pole pitch apart, and these are brought out to two sliprings mounted on, and insulated from the shaft. Stationary brushes pressing on the rings provide a sliding connection between the rotating winding and the stationary terminals of the machine, and so to the external circuit.

One cycle is completed while the tappings move through the distance of two pole pitches, so that in one revolution of the armature the number of cycles gone through will be equal to the number of pairs of poles in the field. The number of cycles gone through in one second is known as the frequency or periodicity, and is equal to the number of pairs of poles multiplied by the number of revolutions per second.

**Electrical Degrees.**—For mathematical treatment the cycle is considered as being divided into 360 degrees, similarly to a circle, the points of zero pressure being at 0, 180 and 360 degrees, the latter corresponding to 0 degrees for the next cycle. Points of maximum pressure are midway between the zero points, or at 90 and 270 degrees. When the field is of only two poles, the pressure between tappings will go through one cycle for each revolution of the armature, and the progress of the cycle in electrical degrees will equal the progress of the armature in geometrical degrees.

With multipolar fields, however, there will be a greater number of electrical degrees per revolution than of geometrical degrees, the latter always numbering 360, while the former will be equal to the number of pairs of poles multiplied by 360.

Stated simply, one pair of poles corresponds to one cycle or 360 degrees, the pressure between tappings going through one cycle while the conductors between them are passing through two pole pitches, so that the distance of one pole pitch, with which the reader is already familiar, equals 180 electrical degrees.

Excepting where specified otherwise, the degrees mentioned throughout the remainder of this book will be electrical degrees, equalling 360 per pair of poles, or per cycle.

**Alternating Pressure from the Lap Winding.**—The maximum pressure obtainable from the lap winding is seen to be that existing between two neutral points situated one pole pitch apart; this, therefore, will be the maximum value of the alternating pressure. Two tappings made to the winding at this distance apart will have the full pressure between them when they are at the neutral points, while midway between the neutral positions the pressure will be

at the point of reversal or zero. Considering the stationary groups of e.m.fs. induced in the winding when it is revolving, the tappings may be looked on as spanning each of these in turn, and as successive groups are in opposite directions, the pressure between the tappings will alternate also.

In a multipolar machine tappings are made at intervals of one pole pitch apart round the winding. Those situated an even number of pole pitches apart have no difference of pressure between them, and are therefore connected together, so forming two groups, each of which is taken to a separate slipring.

In Fig. 12 is shown part of the armature winding and field magnet system of a multipolar machine, corresponding to that represented in Fig. 5. As the tappings rotate with the winding, a series of diagrams might be given showing them in successive positions. These diagrams, however, would be identical except for the positions of the tappings, the signs of the field poles and the directions of e.m.fs. induced being the same in all, therefore one only will serve.

The successive positions of the tappings are shown at the top, or back end connections, the first position being shown directly on the winding, and the succeeding ones projected above it to prevent confusion. By this means the relative situations of the tappings at different parts of the cycle may be readily seen.

Commencing with the position marked 0 degrees, by tracing out the winding it will be found that of the twelve conductors between *a* and *b* there are five having e.m.fs. in each direction, and two in the neutral zones of the field.

The pressure between tappings *a* and *b* will therefore be zero.

In the next position 90 degrees later, there will be ten conductors all having their e.m.fs. in the same direction,

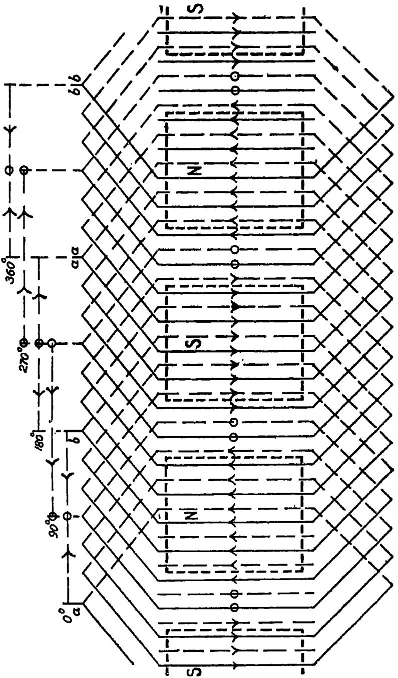



Fig. 12.

from $a$ to $b$ in the winding. The pressure between the tappings will therefore be a maximum, and will be from $b$ to $a$ in the external circuit, as shown by the arrow-heads on the broken line between the tappings.

Proceeding on these lines the complete cycle may be followed, the position at 180 degrees giving zero pressure; 270 degrees maximum in the opposite direction to that at 90 degrees, and 360 degrees zero once more, the section of the winding being now in the same position relative to the field as it was at 0 degrees, but under the next pair of poles. Further movement will then repeat the cycle, and so on for each pair of poles in the field.

By taking a third tapping $aa$ situated 180 degrees ahead of $b$ it may be seen that the pressure between $b$ and $aa$ will be 180 degrees ahead of that between $a$ and $b$. That is, at any instant, that section of the winding between $b$ and $aa$ will occupy a position in the field which will be reached by that between $a$ and $b$ 180 degrees later. The two pressures being displaced by 180 degrees, or half a cycle, will therefore be in opposition at all times. In the position shown for 0 degrees in Fig. 12, both will be zero; at 90 degrees they will be from $a$ and $aa$ to $b$, while at 270 degrees they will be from $b$ to $a$ and $aa$, having reversed at the zero position, 180 degrees.

Sections of the winding between further tappings made at 180 degree intervals will have their pressures corresponding in value and direction with those already considered, being spaced at intervals of 360 degrees from one or other of the first two, and therefore situated similarly with respect to the field. This can be seen from Fig. 13, in which is shown the progress of the tappings of a four-pole winding, taken at intervals of 90 degrees during one cycle.

Observing the directions of the e.m.fs. induced in the conductors, as indicated by the arrow-heads on the circle,

the position at 0 degrees gives zero pressure between the tappings. A small movement of the armature results in the tappings being advanced with respect to the distribution of the e.m.fs. in the winding. There will then be between the tappings more conductors having e.m.fs. in one direction than in the other. The effective pressure will therefore be equal to the difference between these two opposing groups of e.m.fs.

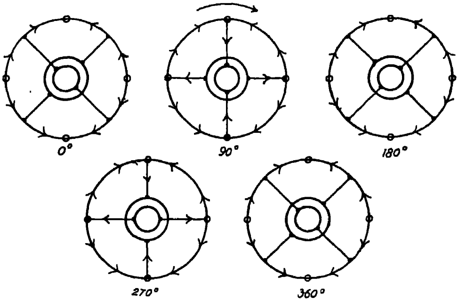



Fig. 13.

As the rotation of the armature continues, the inequality of the opposing e.m.fs. between the tappings increases, and the effective pressure becomes greater until the position shown in Fig. 13 for 90 degrees is reached, when all the e.m.fs. are in the same direction and maximum pressure exists between the tappings. With further rotation the arc of the circle between tappings begins to include a part governed by an opposing arrow, indicating the introduction of opposing e.m.fs. The effective pressure therefore falls until zero is reached once more.

**Diagram of Pressure Wave.**—A diagram can be made which will show the value and direction of the pressure at any part of the cycle.

In Fig. 14 the horizontal line represents time, and on it any convenient length can be marked off to represent the duration of one cycle. The beginning and end of the distance thus marked off will be points of zero pressure, while midway, at the end of the half-cycle, will be another zero point. The instants of maximum pressure will be midway between the zero points, and considering the horizontal line to be also the line of zero pressure, the two maxima will be, one above and the other below the zero line.

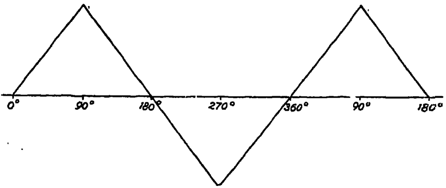



Fig. 14.

With a uniform distribution of the field flux, equal movements of the winding in equal times will bring about equal changes in the pressure between tappings, so that the pressure will rise and fall at a uniform rate between zero and maximum. This is represented by the zigzag line in Fig. 14, the height of the maxima being marked off to a suitable scale of volts, the intermediate heights corresponding to the pressure at any particular part of the cycle, while the reversal of direction is shown by the pressures in successive half-cycles being measured alternately above and below the zero line.

As the cycle progresses uniformly with the increase of time, the base line may be marked in degrees instead of in fractions of a second, the diagram then giving a direct indication, at any point in the cycle, of the movement of the tappings from the position of zero pressure.

From Fig. 14 it will readily be seen that two equal pressures displaced by 180 degrees would be at all times equal in value and opposite in direction to each other, by drawing a second pressure line, or wave, having its corresponding points displaced by half a cycle from those of the first.

**Sine Wave of Pressure.** Such a wave of pressure variation as is shown in Fig. 14 is not by any means of a desirable shape. For a variety of technical reasons there is one particular "wave form," as it is called, which is most suitable. This is known as a "sine wave," and has

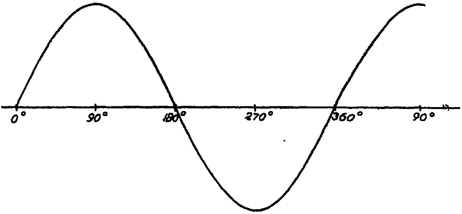



Fig. 15.

the form shown in Fig. 15, in which a certain relation exists between the instantaneous value of the pressure at any part of the cycle, the maximum pressure, and the distance in degrees from the commencement of the cycle. These are related by what is known as a sine law, so that the ratio of the instantaneous value to the maximum is equal to the

sine of the angle of the same number of degrees as that at which the instantaneous pressure is taken.

Thus, when the pressure has advanced 30 degrees from zero, its value is 0·5 of the maximum, 0·5 being the sine of an angle of 30 degrees. At 45 degrees the value is 0·707 and at 60 degrees 0·866, these being the sines of the respective angles.

Comparing the wave of Fig. 14 with that in Fig. 15, it will be noticed that whereas in the former the height of the wave changes at an equal rate at any part of the cycle, in the latter the change of height is unequal at different parts for equal distances on the base line.

In particular it will be observed that the rate of change, as shown by the slope of the curve, is greatest about the zero point in Fig. 15, and least about the maximum, where, in fact, the curve is momentarily horizontal.

Now, in Fig. 14 it was assumed that the e.m.f. induced in the conductors was the same in any part of the field; that is, the rate of cutting the flux by the conductors was uniform over the whole of the field. To obtain a sine wave of pressure, however, it is necessary to arrange that the e.m.f. induced shall vary with the position of the conductor in the field. This is done by shaping the pole faces so that the airgap is wider under the leading and trailing edges than under the centre of the pole, the faces being formed to a larger radius than that from the centre of the face to the centre of the armature shaft. The result is that the flux is denser towards the middle of the pole face owing to the lower magnetic reluctance of the narrower airgap, and by proportioning the airgap suitably any desired wave form may be obtained.

When the armature conductors immediately connected to the tappings are in the neutral zones of the field and the pressure between the tappings is at maximum, further

movement introduces opposing e.m.fs. and so reduces the effective pressure, as explained earlier. With the modified airgaps just referred to, the opposing e.m.fs. are comparatively small, being considerably below the average for the whole group, as the conductors in which they are induced are in the weakest part of the field. The result is that the crest of the wave loses its pointed form, its now flattened shape showing the much more gradual change of pressure about the maximum of the wave. On the other hand, when the pressure between tappings is zero, the e.m.fs. in the two halves of the group of conductors being equal and opposite, further rotation adds to one direction e.m.fs. induced in conductors in the strongest part of the field, and thus having more than the average value. The rate of change of the pressure is therefore increased about the zero of the wave, as is shown by its steeper slope in this region.

**Virtual, or R.M.S. Values.**—Pressures and currents are measured by the effects which they produce under certain conditions.

In a given circuit the power expended is at every instant proportional to the square of the pressure applied, or conversely, the pressure is proportional to the square root of the power. With a continuous pressure the power remains constant while the circuit conditions are unchanged, and the average power is equal to the maximum.

With an alternating pressure, however, the power is continually varying between zero and maximum, so that the average value is less than the maximum. What is required, then, for an alternating pressure, is a nominal value which shall be equal to a continuous pressure producing the same power, and this nominal value will, of course, be less than the maximum.

The average power is equal to the average, or mean, of

the squares of the instantaneous values of the pressure, taken at successive instants throughout one half-cycle. The equivalent continuous pressure is proportional to the square root of the average power, so that the nominal value of the alternating pressure will be equal to the square root of the mean of the squares of the instantaneous values of the pressure throughout one half-cycle.

The same line of reasoning may be applied to the current, as in a circuit of given resistance the power is at any instant proportional to the square of the current. The nominal value of an alternating current, therefore, will be equal to the square root of the mean of the squares of the instantaneous values, taken throughout one half-cycle.

This nominal value is called the "virtual" or "root-mean-square" (R.M.S.) value, and for a sine wave is equal to 0·707 of the maximum value; conversely, the maximum value is 1·41 times the virtual value.

Voltmeters and ammeters used in a.c. practice indicate the virtual values of pressure and current respectively, and as in all ordinary work the assumption is made of a sine wave form, the readings of these instruments must be multiplied by 1·41 to obtain the maximum values.

Subject to such modification as is explained later in this chapter when dealing with power factor, the product of the virtual values of the pressure in volts and the current in amperes will equal the power in the circuit in watts, as in c.c. practice.

**Armature Reactions.**—The armature reactions produced by an alternating current in the lap winding with tappings at 180 degrees, are somewhat different to those from the same winding when supplying a load at continuous pressure. In the latter case the distribution of current in the winding is identical with the e.m.fs. induced, and produces stationary fluxes midway between

the field poles. In the alternator, however, the conditions are different, arising out of the fact that the points where the current is entering or leaving the winding (the tappings) are rotating with the winding.

When the tappings are midway between the field poles, the current, then at maximum, has the same distribution as in the continuous pressure machine, and the effect on the field is the same, a distortion in a forward direction. As the tappings move forward from this position, the centre lines of the armature flux, which coincide with the tappings, move forward also, and the current decreasing at the same time, the distortion becomes less until, when the tappings are under the centre of the poles, the current is zero and the field flux therefore undisturbed.

As the tappings move forward from this zero position fluxes arise of opposite sign to those of the field poles, and as the centre lines of armature flux and field flux do not now coincide, the latter is distorted in the direction of rotation once more, the distortion increasing until the tappings are midway between the poles, when the armature current is at maximum and the distortion therefore greatest.

The total result is that the field distortion is intermittent, the flux swinging forward and back to normal for each pulsation of the armature current, or twice in each cycle.

**Load Torque.**—As the power output varies between zero and maximum during each half-cycle, the load torque on the machine will pulsate likewise, twice in each cycle.

Fleming's right- and left-hand rules show that when the current in an active conductor is in the same direction as the induced e.m.f. it produces a force opposing the motion of the conductor, or a load torque. When the current is in the opposite direction to the induced e.m.f. the resulting force is in the direction of motion, or a motoring torque.

Now the current in any section of the winding under consideration will flow in accordance with the total, or effective, pressure between the tappings.

When the pressure is at maximum all the induced e.m.fs. are in the same direction as the current and the torque is wholly a load torque. At any other instant between maximum and zero there are certain conductors the e.m.fs. in which are in opposition to the effective pressure between tappings, and consequently in opposition to the current. These conductors will therefore be acted on by a motoring torque in opposition to the load torque on the other conductors. The load torque will always be the greater of the two, however, as the current is always in the direction of the induced e.m.fs. in the larger number of conductors, and the effective torque on the armature at any instant will be equal to the difference between the two opposing torques, and will be a load torque.

The value of the effective torque at any instant is proportional to the power at that instant, and as the latter is equal to the product of the instantaneous value of the volts and amperes, a curve may be constructed which will show the variations of the power or the torque. This curve is shown in Fig. 16, and is a sine curve of twice the frequency of the curves from which it is derived. As the pressure and current are both in the same direction at any instant, they will always be positive with respect to each other. Their products, therefore, will always lie on the same side of the base line of the power curve, showing that the power, although it falls to zero twice in each cycle, never reverses.

The average height of the power curve over one cycle is equal to one-half its maximum height.

**Effect of Phase Displacement.**—So far it has been assumed that the current in the winding has been in phase

with the effective pressure. That is, the two have gone through the cycle of changes together, passing through zero and maximum at the same instants as each other.

In practice, however, it often occurs that the pressure and current are not in phase, there being a displacement in

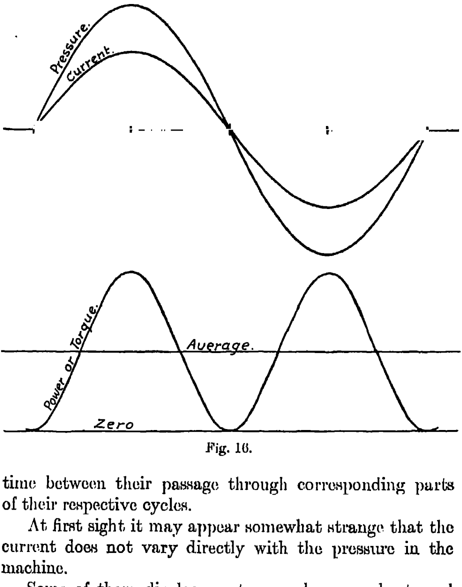



Fig. 16.

time between their passage through corresponding parts of their respective cycles.

At first sight it may appear somewhat strange that the current does not vary directly with the pressure in the machine.

Some of these displacements may, however, be traced

to the presence, somewhere in the system connected to the machine, of other sources of alternating pressure which are out of phase with that generated by the machine under consideration.

In these circumstances the effective pressure acting in the system is not solely that due to our generator, but the result of the combination of this and the pressure from the other source or sources referred to.

The current then flows in accordance with this resultant, as it is called, and may therefore be displaced in phase from the pressure in the generator, this depending on the phase relationship between the latter and the resultant.

The foregoing applies to those cases where the current is displaced behind the pressure, and also to some of the cases where the current precedes the pressure.

In other instances of the latter displacement this is the result of a phenomenon which is to be observed in a circuit when subjected to an alternating pressure, while the condition may even arise when the circuit is incomplete, that is when no current would be produced by a continuous pressure.

Consideration of the causes of two alternating pressures or currents in the same circuit, and the resultant arising therefrom, will be deferred to a later section, our object being now to deal with the effects of a phase displacement between current and pressure on the operation of the machine.

In the first place, the amount of displacement may be measured either in time or degrees, as the progress of the cycle is uniform with that of time; it is the invariable practice to use degrees.

When the current precedes the pressure it is said to be "leading," while a displacement in the other direction is known as "lagging."

Thus if the current is lagging by 30 degrees, when the pressure has reached maximum in a given direction the current will only be at 60 degrees from zero in the same direction, and so on throughout the cycle.

In drawing the sine curves showing pressure and current in phase the same scale of degrees serves for both, as both begin the cycle at the same instant.

When there is a displacement between them, however, a different starting point must be used for each curve, the two points being separated by the correct distance corresponding to the number of degrees displacement.

For example, with a current lag of 30 degrees, the commencement of the pressure cycle would occur on the zero line a distance equal to one-twelfth part of a cycle, or 30 degrees before the beginning of the current cycle, as in Fig. 17.

The current curve as a whole is displaced to the right from the pressure curve, showing the later occurrence of its series of changes as compared with those of the pressure.

As the maximum current no longer coincides with the maximum pressure the maximum torque will not be as great as when these two occur at the same instant.

Furthermore, the torque will be at zero four times in each cycle, while at certain times the pressure and current will be in opposite directions, producing a motoring torque.

When the pressure is zero the current has half its maximum value, but as at this instant the armature tappings are equidistant on either side of the neutral points of the winding the conductors between them are divided into two equal groups in fluxes of different sign and therefore producing opposing torques; consequently the effective torque is zero.

Again, when the current is zero there is, of course, no torque although the pressure is at half maximum value.

The torque curve during one cycle, then, consists of two periods of load torque each followed by a short interval

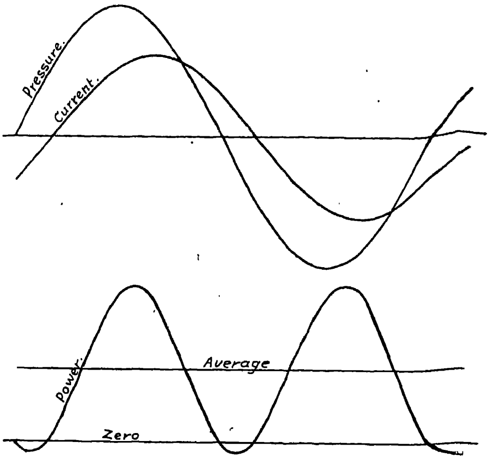



Fig. 17.

of motoring torque, the torque passing through zero at the four points of reversal.

Multiplying together the instantaneous values of the two curves in Fig. 17, as before, the torque curve is as shown in the figure.

Where the two curves are on either side of the zero

line one is negative to the other, so that their product will be negative; this causes the torque curve to lie, at those parts, below its zero line, showing the reversal of torque.

As compared with Fig. 16, it will be seen that the average load torque over one cycle will be less, partly owing to the smaller maximum and partly to the periods of motoring torque, so that the power required to drive the generator will be less when the current is out of phase.

Under these conditions the machine will be generating during parts of the cycle and motoring during other parts, delivering power to and receiving power from the rest of the system to correspond.

The effective output will be equal to the difference between the output and the input, and will therefore be less for a given pressure and current the greater the phase displacement between these two.

When the current is displaced by 90 degrees, as in Fig. 18, the torque curve will be symmetrical about the zero line, the load and motoring maxima having equal values. The average torque on the armature will then be zero, the machine generating and motoring alternately during successive quarter cycles.

At the instant of maximum current the conductors will be equally divided between fluxes producing opposite effects and the pressure will therefore be zero, while when the conductors are all in fluxes producing cumulative effects and the pressure a maximum the current is zero, both conditions producing zero torque.

With leading current the effect is the same as with lagging, a reduction of the effective output for a given value of the current.

**Power Factor.**—In order to find the actual power given out by an alternator it is not sufficient merely to multiply together the values of the volts and amperes as with

continuous current. Doing this gives what is known as the apparent power, and a correcting factor must be applied to allow for any phase displacement between current and pressure, before the actual power can be known.

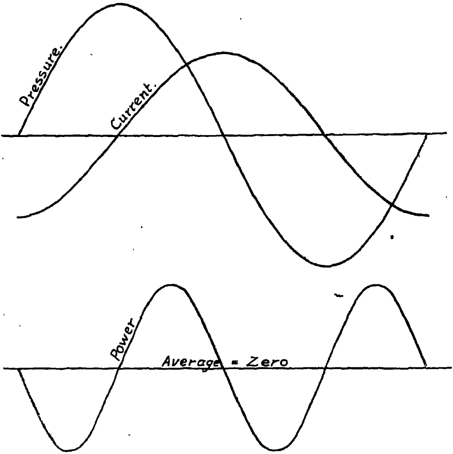



Fig. 18.

This is the Power Factor, and is the ratio between the actual power and the apparent power.

When current and pressure are in phase, the actual power equals the apparent power and the power factor is 1·0 or unity.

With lagging or leading current the power factor becomes

less as the displacement increases, until when the latter equals 90 degrees the power factor is zero and the actual power nil.

It will be clear that for a given pressure and current the power is greatest when these are in phase, while conversely, for a given power the current will have the smallest value when it is in phase with the pressure, any displacement requiring an increase of current to maintain the same effective power output.

Instruments are in use for indicating the power factor directly on a scale graduated from 0 to 1·0, and by multiplying together the readings of the voltmeter, ammeter, and power factor indicator, the actual power is found.

Indicating watt-meters are sometimes used to give the value of the actual power by direct reading; the power factor will then be equal to the actual watts divided by the product of volts and amperes.

In order to distinguish between real and apparent power the former is reckoned in watts and the latter in volt-amperes, the kilo-watt (kW) and kilo-volt-ampere (kVA) being derived from these.

The importance of the power factor will be evident when it is remembered that from the electrical point of view the loading of alternators, cables, or other apparatus is limited by the current which they will carry without overheating.

The nearer the power factor is to unity, then, the larger is the amount of power which such apparatus can deal with, and the greater the efficiency with which they may be utilised.

The expression "wattless current" is one which is often loosely used in connection with the subject of power factor, and may mislead the non-mathematical reader.

This is an abbreviation of "wattless component of current," and arises from a practice employed in certain

calculations of considering a current, when out of phase with the pressure, to be made up of two separate components, the calculations being facilitated thereby.

One of these components is assumed as being in phase with the pressure, and is known as the power component; the other, displaced by 90 degrees from the pressure, is the wattless, or idle component.

The power component is equal to the actual current multiplied by the power factor, so that the product of the power component and the pressure equals the watts real power in the circuit.

The wattless component, displaced by 90 degrees, has no power associated with it, and if multiplied by the pressure, the product is known as the wattless volt-amperes.

It is particularly to be observed that although the actual current is larger than either of these assumed components, yet it is less than the sum of the two when these are added directly.

Mathematically, the power factor is equal to the *cosine* of the angle of current displacement, while the wattless component is equal to the product of the current and the *sine* of the same angle.

**Reversal of Power and Torque.**—Returning to the torque or power curves in Figs. 16, 17, and 18, when the current and the pressure are in phase this curve lies wholly on one side of the zero line, while a displacement of the current causes a part of the curve to appear on the other side, the amount increasing with the angle of displacement until 90 degrees is reached, when the curve is equally disposed on either side of the zero line.

If the current is displaced by more than 90 degrees the result is a reversal of the effective power from its former direction, the curve now lying more on the motoring side of the zero line, until when the current is 180 degrees out

of phase, or in opposition to the pressure, the torque is wholly a motoring one.

The force on the armature conductors, instead of opposing the rotation, now assists it by acting in a forward direction, the machine taking power from the external system and running as a motor.

It will, of course, be understood that only when another alternator is connected to the system can this state of matters be brought about, the interaction of the pressures from the two sources causing the current to be displaced more than 90 degrees from that generated by the machine under consideration, this not being otherwise possible.

The way in which this is done will be dealt with more fully later on, it being desired now to call attention to the following relations between the current, pressure, and power or torque in an alternator.

When current and pressure are in the same direction (no phase displacement) the power is a maximum, generated or output.

When maximum of one corresponds with any value of the other less than maximum but in the same direction (lag or lead less than 90 degrees), the power is smaller for the same current.

When maximum of one coincides with zero of the other (90 degrees lag or lead) the power is zero.

When maximum of one corresponds with any value of the other, less than maximum and in the opposite direction (lag or lead more than 90 degrees), the power is input and the torque motoring.

When maximum of each occurs at the same instant, but in opposite directions (180 degrees or maximum displacement), the input of power and motoring torque is a maximum for a given current.

**Armature Reactions of A.C. Motor.**—As with the c.c.

machine, so in the alternator the poles of the armature flux change their sign with the reversal of the torque from generating to motoring.

The armature current being in the reverse direction to the effective pressure between tappings, the armature poles are of the same sign as the field poles behind them; the main flux is therefore distorted in the opposite direction to that of rotation.

**Effect of Lag or Lead on Armature Reaction.** The centre lines of the armature flux correspond with the position of the tappings to the winding, as these are the points on either side of which the current is in opposite directions in the conductors.

The position of maximum pressure is when the tappings are midway between the field poles, and when the current maximum occurs at the same instant the armature cross flux, of the same sign as the next poles ahead, distorts the main flux in the direction of rotation.

When the current is lagging, it reaches maximum after the armature has passed the position of maximum pressure, so that the poles of the armature flux are no longer equidistant between the field poles; they will be nearer the next poles ahead.

As a result the distortion is unequal, the weakening of one pole tip exceeding the strengthening of the other, the flux being reduced as well as distorted.

The greater the angle of lag the further on will the armature have moved before current maximum occurs, and the more unequal the distortion, that is, the greater will be the reduction of the total flux.

At 90 degrees lag the centre lines of armature poles and field poles will coincide at maximum current and the weakening of the field will be greatest.

With a leading current the field flux will be increased,

as the armature current and flux will reach maximum before the armature reaches the position of maximum pressure, the centre lines of the armature fluxes then being nearer to the field poles behind.

When the machine is operating as a motor the conditions are reversed, the armature fluxes being of opposite sign to the field poles ahead of them.

Lagging current will strengthen the field by bringing armature and field poles of unlike sign more nearly in line, while conversely leading current, by causing poles of like sign to approach each other, has the effect of weakening the field.

To summarise the whole of these reactions.

In a generator the field flux is distorted in the direction of rotation, while in a motor the distortion is in the opposite direction.

Lagging current weakens the field of a generator and strengthens that of a motor.

Leading current strengthens the field of a generator and weakens that of a motor.

All these effects are periodic, with a frequency twice that of the armature current, as they increase and decrease with the rise and fall of the current in each half-cycle.

# CHAPTER V

*VECTOR DIAGRAMS, INDUCTANCE, AND CAPACITANCE*

**Resultant of Two Sine Curves.**—To arrive at the resultant of two alternating pressures we may proceed by drawing the sine curves of each, with the proper phase displacement between them.

At any instant the resultant pressure will be equal to the sum of the two if in the same direction, or their difference if they are in opposite directions, in the latter case the resultant being in the direction of the greater of the two.

By measuring the distances of the two curves from the zero line at successive instants and adding or subtracting them according to their relative directions, a third curve may be constructed with the values thus obtained, which will be the sine curve of the resultant and will have a phase displacement from one or both of the others.

If the two pressures are exactly equal and have a displacement of 180 degrees they will balance each other at every instant and the resultant will be zero.

Two unequal pressures in opposition thus will have a resultant with a maximum value equal to the difference between the two fundamental maxima, this resultant being in phase with the greater of the two and in opposition to the smaller.

In Fig. 19 the heavy line shows the resultant of two equal pressures displaced by 38 degrees from phase

opposition, the maximum of $E_1$ occurring 38 degrees later than that of $E_2$ in the opposite direction.

Maxima of each in the same direction occur at intervals of 218 degrees and 142 degrees alternately, $E_1$ lagging behind $E_2$ by the former angle and leading $E_2$ by the latter angle.

The resultant is equally displaced from both the fundamentals $E_1$ and $E_2$, owing to their being of equal magnitude.

Were they unequal the resultant would be more nearly in phase with the larger of the two, this having the greater effect in the circuit.

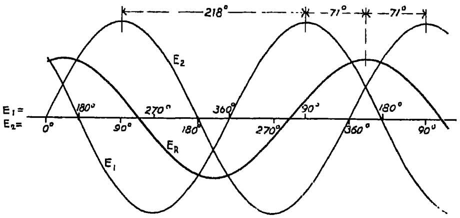



Fig. 19.

This method of dealing with alternating quantities is somewhat laborious, besides giving a result which does not present such a clear picture of the relationships involved as can be obtained by other means. It has been given, however, as a preliminary to the introduction of the vector diagram, which is used for the same purpose.

**The Vector Diagram.**—It is not proposed to go into the theory of the vector diagram, but to say sufficient about it to enable the reader to have some idea of the propriety of its application to the subject before him.

A vector may be considered as a straight line which is

rotating in an anti-clockwise direction about a point, known as the "point of origin," at one of its ends. The motion is similar to that of one spoke of a wheel, the free end describing a circle, as in Fig. 20.

If the length of the vector represents to some scale the maximum value of an alternating pressure which varies according to a sine law, the vertical distance of its end above or below the zero line horizontally through the point of origin, will be equal on the same scale to the instantaneous value of the pressure at that point in the cycle, measured in degrees of rotation from the position 0°, which corre-

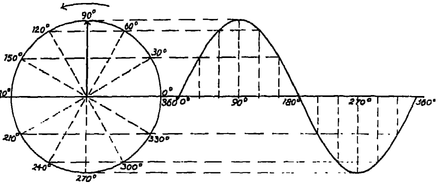



Fig. 20.

sponds to the commencement of the cycle. The ratio of these vertical distances to the length of the vector is, in fact, the sine of the angle through which the vector has moved from 0°, which suggests at once the derivation of the sine curve, as stated on its first introduction in Chapter IV., and shown in Figs. 15 and 20.

Two pressures of similar frequency may be represented by two vectors rotating about a common origin, and making an angle with each other equal to their displacement in degrees, as $E_1$ and $E_2$ in Fig. 21. The phase angle is the same as between the two pressures in Fig. 19, $E_1$ leading $E_2$ by 142 degrees.

The passage of each of these through the zero and maximum positions will, of course, be separated by the angle between them, while at any instant the vertical distances of the ends of the vectors from the zero line will correspond to the instantaneous values of the two pressures, each being at a different part of its own cycle.

The resultant of $E_1$ and $E_2$ is found by drawing a line from the free end of one of them, parallel to the other and of equal length, then joining the end of this third line to the common point of $E_1$ and $E_2$.

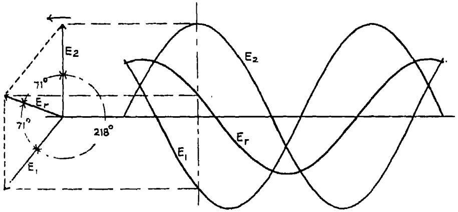



Fig. 21.

This last line, marked *Er* in Fig. 21, will equal in length the maximum value of the resultant, to the same scale as the fundamentals, while its displacement from either of them will be equal to the angle it makes with them.

To the right of Fig. 21 are reproduced the curves from Fig. 19, the particular instant shown in the vector diagram corresponding to the vertical broken line through the curves : $E_2$ is at 90 degrees or maximum, $E_1$ at 232 degrees rising towards maximum in the opposite direction, and *Er* at 161 degrees falling towards zero.

Any other instant would be shown by the vectors having

rotated through the necessary angle, while still retaining the same relationship to each other.

If in Fig. 21 one of the pressures, say $E_1$, was greater than the other, it can easily be seen that the resultant would be advanced in phase so as to lag behind $E_1$ by a smaller angle, the lead from $E_2$ being correspondingly increased.

Reducing the angle between the two fundamental pressures has the effect of increasing the resultant until, when the former are in phase incidence—that is, have no displacement between them—the resultant is equal to the sum of the two.

Increasing the angle between them has the opposite effect, the resultant diminishing until they are in phase opposition, when it equals the difference between them.

It will be appreciated by the reader that these relationships can be more easily worked out, and the result more readily presented to the eye by means of vectors than by working from the sine curves, and therefore he should familiarise himself with the use of these diagrams, which, after all, to the degree in which they are used here, are very easily understood.

As the lengths of the vectors correspond to the maximum values of the pressures, by concerning ourselves with these only, instead of the instantaneous values at different parts of the cycle, we may dispense with the zero line, and the diagram may be drawn in any position, so long as the correct scale lengths are applied to the vectors and the proper angle maintained between them.

Further, the diagram may be used to represent virtual values by reason of the fact that these bear a definite ratio to the maximum values, so that if the same scale is used the vectors will all be proportionally shorter, and their relative values and phase angles unchanged.

To be strictly correct, the expression " vector diagram "

has no meaning when applied to a diagram of virtual values, as these do not vary according to a sine law; on this account they are often called clock diagrams, although both terms are in common use.

Alternating currents may also be dealt with by vectors in the same manner as pressures, while vectors representing both of these may be used in one diagram where it is desired to observe the relationships existing between them, each being drawn to its own scale of amperes and volts respectively.

One or two further examples will be given illustrating points already dealt with in considering the effect of current displacement.

In Fig. 22 (*a*) a current, I, lags behind the pressure E. If I is projected perpendicularly on to E the length I*p* is equal to the power component of I; it is equal to I multiplied by the power factor, and represents the value which the current would have for the same actual power if the power factor were unity.

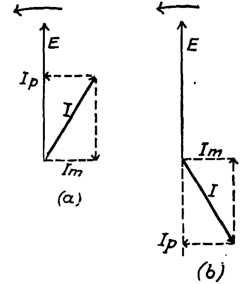



Fig. 22.

A similar projection of I on to a line at right angles to E gives the length I*m* equal to the wattless component, and this represents the current which, if displaced by 90 degrees from the pressure, would produce a similar demagnetising effect on the field of the alternator as is produced by the current I.

For this reason it is sometimes called the demagnetising component if lagging, or magnetising if leading.

As a current which is in phase with the pressure has no idle component, so one displaced by 90 degrees has no power component, the projection of the current vector on to the pressure vector giving zero.

If the current is displaced by more than 90 degrees, its power component falls on to the reversed projection of the pressure vector as in Fig. 22 (*b*), showing that the power is input to the source of the pressure E.

As already pointed out, this condition cannot arise unless there is more than one generator in the system.

In dealing with more than two alternating pressures or currents by means of vectors, first combine two of them and find their resultant. Then combine this resultant with the third vector, this second resultant with the fourth vector and so on. The final resultant, when all the vectors have been included, is the resultant of them all. In practice this simplifies into drawing the various vectors end to end, the second from the end of the first, the third from the end of the second, and so on, with the necessary angle between the direction of each vector and its successor. The resultant of the whole, then, is a line drawn from the free end of the last vector to the point of origin, as in Fig. 23.

When the result is to form a closed polygon, the end of the last vector arriving at the point of origin, the resultant is zero, the various pressures or currents exactly balancing each other in the circuit. A case of this kind occurs in the lap-connected armature winding, where each conductor, considered separately, has induced in it an alternating e.m.f. The phase angle between successive conductors is equal to 360 divided by the number of conductors per pair of poles, and the e.m.fs. being equal, the diagram forms

a regular polygon having as many sides as there are conductors per pair of poles.

The pressure between any two tappings to the winding is then found by drawing a line between two angles of the polygon the requisite distance apart. The length of this line, to the same scale as the vectors, is the resultant of the e.m.fs. in the conductors between the two tappings.

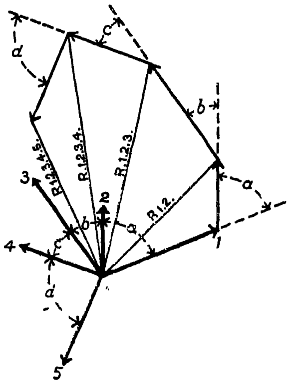



Fig. 23.

Now in a regular polygon, all its angles will lie on the same circle, so that we may simply draw a circle with a diameter representing, to a scale, the pressure between points 180 degrees apart in the winding. Then the pressure between any pair of tappings to the winding will be represented by a line joining two points on the circle the corresponding number of degrees apart.

### Inductance

It has been stated when the current lags behind the pressure in a generator this may be traced to the existence of other sources of alternating pressure in the circuit.

That this is so even when there is no other alternator, will appear from the following considerations.

In earlier chapters we have considered an e.m.f. as being induced when a conductor cuts a magnetic flux, but this is true only when the cutting is done in such a manner as to vary the total flux linked with the conductor.

Taking one turn of the lap winding which we have been studying, it will be seen that the flux through it varies in value from a maximum of one sign to a maximum of the other sign. When the coil is linked with a flux of all one sign the e.m.f. induced is zero, the conductors then being in the neutral zones, while when the flux through the coil is half of each sign, the conductors being under the middle of the pole faces, the rate of change of the flux is greatest and the e.m.f. induced is a maximum.

It is equally true, therefore, to say that when the flux linked with a conductor changes in value there is an e.m.f. induced in the conductor, the value of this depending on the rate of change of the flux.

Now, we have seen that a conductor carrying a current is surrounded by a magnetic flux, the density of which varies with the current.

This flux will be steady while the current remains steady, but if the current varies, the flux linked with the conductor will vary also, and in so doing will induce an e.m.f. therein. This is known as the e.m.f. of self-induction, or reactive e.m.f., and its direction will be such as to oppose the variation of the current, an increase of current causing an opposing e.m.f. and a decrease an assisting e.m.f.

This e.m.f. will only be present during the actual time that the current is changing in value, and disappears as soon as the current becomes steady once more.

If the current is alternating, the flux and consequently the e.m.f. of self-induction will be alternating also.

The times of maximum rate of change of the flux will be when the current is passing through zero, while when the current is at maximum the rate of change will momentarily be zero, and likewise the reactive e.m.f.

If curves are drawn to represent these quantities, current

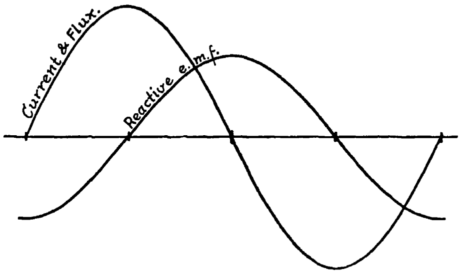



Fig. 24.

and flux, and reactive e.m.f., we get the result shown in Fig. 24. It will be observed that when the current begins to fall from maximum the induced e.m.f. tends to oppose the change and is therefore shown as rising from zero in the same direction. There is thus a displacement of 90 degrees between the current and the e.m.f. of self-induction, the former leading the latter by that angle.

The value of the reactive e.m.f. in a given circuit will depend on the current, as the rate of change will be greater

with a larger current. Similarly, with a given current in a circuit, the reactive e.m.f. will be greater the higher the frequency, as with the shorter time interval between successive maxima in opposite directions, the rate of change will be greater.

The reactive e.m.f. combines with the pressure generated by the alternator, the resultant of the two becoming the effective pressure in the circuit, and the current flows in accordance with this resultant.

If it were possible to have a circuit with no inductance the current would be exactly in phase with the pressure.

The presence of inductance causes the reactive e.m.f. to arise, lagging behind the current by 90 degrees; the resultant of the two pressures will therefore lag behind the generator pressure, and so also will the current.

The greater the reactive e.m.f. the more will the resultant lag and the lower will be the power factor.

This is shown in the form of a vector diagram in Fig. 25 (*a*), where $E_r$ is the resultant of $E_x$, the reactive pressure, and $E_a$ the applied pressure. The current is in phase with $E_r$ and $a$ is the angle of lag. Diagram (*b*) shows the effect of an increase in $E_x$, $E_r$ being smaller and the angle of lag greater. Another way of looking at the matter is shown in (*c*) of the same figure. In this the applied pressure $E_a$ is considered as being made up of two components, one $E_{ax}$ which balances the reactive pressure, being equal and opposite thereto; and the other $E_r$ which is employed in producing the current through the resistance of the circuit, and is in phase with the current. If the reactive pressure becomes greater a larger component of $E_a$ is required to neutralise it and the other component $E_r$ decreases.

In a circuit where the resistance is negligibly small compared with the inductance, the reactive and applied pressures are practically equal. The applied pressure is

then almost wholly employed in overcoming the reactive pressure, and the two are 180 degrees apart. The current lags by approximately 90 degrees and the power factor is correspondingly low. Under these conditions energy is being stored up in the magnetic field linked with the circuit during one quarter cycle, and returned to the generator during the next.

The inductance of a straight conductor is comparatively small, but is increased by the presence of iron in the

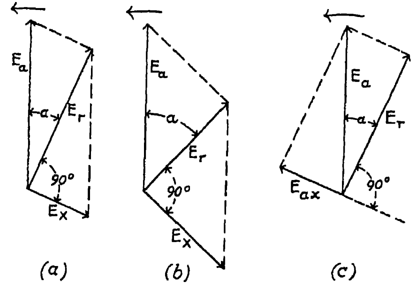



Fig. 25.

vicinity, owing to the higher permeability of the latter increasing the flux. If the conductor is in the form of a coil the flux due to each turn will link with all the turns and the inductance will be increased accordingly, owing to the greater number of linkages, while a coil with an iron or steel core will naturally have a greater inductance than a similar coil with a non-magnetic core.

Coils of this kind, known as reactances or choking coils, are often used where it is required to limit the current in a circuit, the effective pressure being reduced by the

reactive pressure set up by the coil. These coils have the advantage over resistances for the same purpose, that their resistances may be made small and the heating losses kept low.

### Capacitance

When two alternators are connected in parallel the relation between their pressures may be such as to cause the current to lead the pressure in one of them.

There are other circumstances, however, which may result in a leading current where only one alternator is concerned, these arising from what is known as capacitance in the cables, etc., connected to the machine.

In order to see how this comes about we will consider a piece of apparatus called a condenser, which is specially intended to produce a capacitance effect.

In this, two plates of some conducting material separated from each other by an insulating substance, are connected one to each of the terminals of a source of electrical pressure. When the pressure is applied there will be no current through the condenser on account of the circuit being broken by the insulator, but the plates will become charged, one positively and the other negatively, the amount of the charge being proportional to the applied pressure.

As long as the pressure is maintained the charge will remain, any variations in the pressure producing corresponding variations in the charge.

The result of this is that every change in the pressure is accompanied by a current in the conducting parts of the circuit, electricity flowing in one direction or the other as the charge varies.

If the pressure applied to the condenser is alternating the charge will alternate also, the direction of the charge and the signs of the plates reversing with the reversal of pressure, thus producing an alternating current in the

circuit, and this current can be shown to be leading the applied pressure by 90 degrees.

The amount of the charge being proportional to the pressure, both these quantities may be represented by the same curve, as in Fig. 26, while the slope of the curve will indicate the rate at which the charge is changing in value at any instant.

As the pressure approaches maximum in a given direction the charge is building up and the current corresponds in direction to the pressure. When maximum

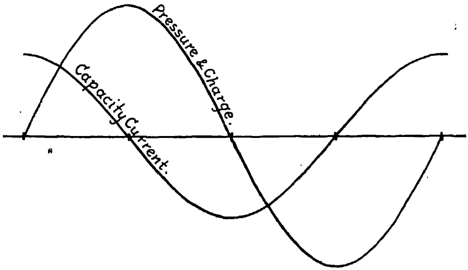



Fig. 26.

pressure is reached the charge is complete and charging ceases, the current therefore being zero at that instant.

On the pressure beginning to fall from maximum the charge is reduced, the current commencing to flow in a direction opposite to the pressure, until when the latter is passing through zero, the rate of change of the charge, that is the current, is a maximum.

Charging then begins in the other direction, corresponding to the reversal of pressure, and as the charge approaches maximum the current falls to zero once more.

The curve showing the variation of the current, or the rate at which the charge changes, is seen to lead the pressure curve by 90 degrees, as stated above.

In general, apart from condensers designed and constructed to operate as such, capacitance effects exist between any parts of a circuit or system which are at different potentials, and with long transmission lines on a.c. systems the charging current becomes a factor of importance in operating practice.

With a pure charging current, energy is being alternately stored in the condenser and returned to the alternator, so that the average power taken over one cycle is zero.

As it is impossible, however, for any conductor to be wholly without resistance, a small loss occurs from the passage of the charging current through the conducting parts of the circuit. This, together with losses which are associated with the dielectric, or the insulator between the conducting parts, results in the output from the alternator during one cycle being larger than the input; the power factor therefore being greater than zero, and the current leading by less than 90 degrees.

In a circuit which is transmitting power there is always present a charging current, however small, and this which by itself would lead the pressure by 90 degrees, combines with the load current, the actual current being the resultant of the two.

Inductance and capacitance effects tend to neutralise each other, but in ordinary practice the inductive effect usually predominates so that the current lags, although not to the extent it would do if the system had no capacitance.

It will be observed that inductance effects depend entirely on the current, while capacitance effects arise solely from the pressure.

# CHAPTER VI

## *POLYPHASE MACHINES*

**Production of Polyphase Pressures.**—A supply derived from a machine having armature tappings at 180 degrees only is known as single-phase, and requires two line wires for transmission. Armature windings may, however, have tappings less than this distance apart, and will give a series of pressures differing in phase from each other. Such machines are called polyphase and have 3, 4, or 6 terminals, according to whether the tappings are at 120, 90, or 60 degrees. Sections of the winding between adjacent tappings are called phases, the number of phases being equal to the number of tappings per pair of poles; the machine being styled 3-phase, 4-phase, or 6-phase accordingly. Rotary converters are invariably polyphase machines, the single-phase converter possessing characteristics which render its use undesirable.

In any polyphase machine the armature winding is divided evenly by the tappings, so that the pressures between adjacent tappings are all equal, while the angular displacement between the phase pressures is equal to the number of degrees between tappings. Thus in a 3-phase system there are three equal pressures following each other at intervals of one-third of a cycle or 120 degrees; in a 4-phase system, four pressures with 90 degrees between them; and in 6-phase, six pressures at intervals of 60 degrees.

In Fig. 27 the circles represent two-pole windings with 3, 4, and 6 tappings. The pressure between tappings equally on either side of the neutral points is zero, while phases midway between the neutral points are at maximum.

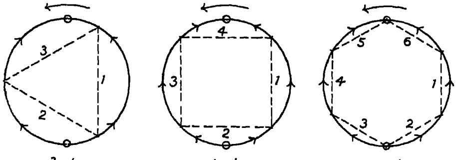



Fig. 27.

As the armature rotates, the phases will each in succession arrive at the position of maximum in a given direction, and the order in which they do this is shown by the numbering of the phases. This is seen to run in the opposite direction to that of the armature rotation.

**Relative Values of Polyphase Pressures.**—The relation between the pressures obtained with differently spaced tappings can be shown by the vector diagram for the lap winding, described in Chapter V., and given in Fig. 28. The pressure between 180 degree tappings, represented by the diameter of the circle, is taken as unity, and the smaller pressures expressed as fractions of this. The same proportions hold good, of course, for either maximum or virtual values.

In the 3-phase machine all the tappings are equally spaced and only one pressure is available, whereas in the 4-phase and 6-phase machines there are alternative groupings providing different pressures.

With 90 degree tappings each is that distance from its

next neighbours, but is in addition 180 degrees from the next but one, and there are thus two distinct values of pressure available. The tappings may be considered as falling into one group with 90 degree intervals, or as two pairs at 180 degrees with a displacement of 90 degrees between the pairs. The machine is therefore of four or two phases according to which view is taken; in rotary converter practice these are always called 2-phase, as they are run from transformers having 2-phase secondaries.

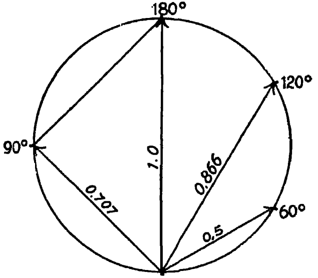



Fig. 28.

In the 6-phase machine there are tappings 60, 120, and 180 degrees apart, and three different pressures. The armature may be considered as having six tappings at 60 degree intervals, two groups of 120 degree tappings, or three pairs of 180 degree tappings.

In the first view the machine is of six phases, in the second of two 3-phase systems interlinked and with 180 degrees displacement between them, and in the last of three single phases displaced by 120 degrees. These

are represented in Fig. 29, each being indicated by a different style of lining.

The subjoined table gives the relationship existing between the pressures with variously spaced tappings in terms of each other.

When the pressure between certain tappings is known, find the column headed by the number of degrees between those tappings. In that column will be found the factor by which the known pressure is to be multiplied to find the

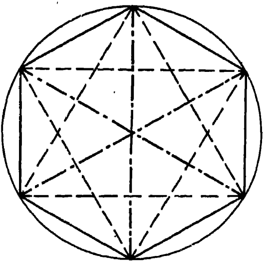


Fig. 29.

pressure between tappings spaced at distances given in the right-hand column.

| 180° | 120° | 90° | 60° | |
|---|---|---|---|---|
| 1·0 | 1·15 | 1·41 | 2·0 | **180°** |
| 0·866 | 1·0 | 1·22 | 1·73 | **120°** |
| 0·707 | 0·82 | 1·0 | 1·41 | **90°** |
| 0·5 | 0·58 | 0·707 | 1·0 | **60°** |

For example, if the pressure between 180 degree tappings is known, multiply by 0·866 for that between 120 degrees, 0·707 for 90 degrees, and 0·5 for 60 degrees.

**Pressures, Current, and Power in Polyphase Machines.**

—In order to obtain a basis for comparison a machine giving a virtual pressure of 100 volts between 180 degree tappings will be considered. The load will be assumed as of 1,000 watts, and the pressures, armature current, and line current worked out for single and polyphase systems.

For the sake of simplicity it will be assumed that the field is of two poles and the power factor unity. As a single-phase machine the line pressure will be 100 volts and the current 1000÷100 or 10 amps., 5 amps., in each path through the winding.

**Two-phase.**—We may proceed by either of two methods, one by treating the machine as of four phases, and the other as of two.

In each case the total power has to be divided equally between the phases, and in the first method the watts per phase in our example equal one-fourth of 1,000, or 250. Dividing this by the phase pressure 70·7 volts we get 3·54 amps., as the armature current per phase.

The line current will be the resultant of that in two adjacent phases with 90 degrees displacement, and will equal 1·41 times 3·54, or 5 amperes.

Considering the machine as of two single phases the same result is obtained. In this case the watts per phase will be 500, which divided by the full pressure of 100 volts gives a line current of 5 amps., or 2·5 amps., in each path through the winding for each phase.

The currents of each phase flow in the one winding and having a displacement of 90 degrees their resultant will be equal to 1·41 times 2·5, or 3·54 amps., as before.

It will be seen that for a given load the ratio between the armature current in the single-phase and 2-phase machines is as 5 to 3·54 or 1 to 0·707. This means that with the latter the heating losses will be smaller for the

same load, or conversely that the machine will give a greater output for the same losses.

The effective torque will be the resultant of the single-phase torques in the four phases of the winding. Phases which are 180 degrees apart will have their maximum torque at the same instant, so that the curves for these will be super-imposed on each other, giving a resultant torque curve of twice the maximum value of either of them singly.

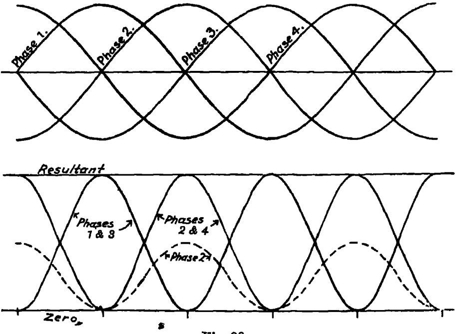



Fig. 30.

There being two such pairs of phases we get two single-phase torque curves each having a maximum value of twice that of one phase, and with a displacement of 90 degrees.

Fig. 30 shows the curves for the current, and power or torque for a 2-phase machine, the power factor being unity and the current and pressure in phase.

By adding together the vertical heights of the torque curves at every instant the resultant is found to have a

steady value equal to the maximum of one of them. The torque due to one phase is given by the broken line curve.

Proceeding on the assumption of there being two phases in the machine the same result is obtained.

Taking the separate torques in Fig. 30 the average of any one of these is equal to one-half its maximum, and from this it will be seen that the total is divided equally between the phases.

The uniform value of the torque in a polyphase machine is of special importance, inasmuch that when used as a motor such a machine is not so liable to "lose synchronism" or be "pulled out of step" by changes of load as is the single-phase machine with its pulsating torque.

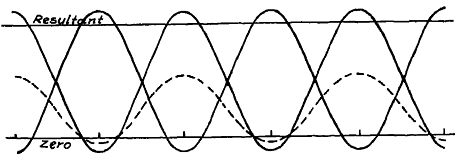



Fig. 31.

As far as individual phases are concerned the effect of current lag or lead is a reversal of the torque during parts of the cycle. Owing to the displacement between the phases, however, when one pair are exerting a reversed torque the other pair are at or near maximum in the other direction, with the consequence that the effective torque at the armature shaft, although reduced, does not reverse at any part of the cycle.

In Fig. 31 are given the torque curves for a power factor of 0·8 corresponding to a current displacement of about 37 degrees. The torque in one of the four phases is shown

by a broken line, as before, the full lines giving the resultants of two such.

From this it will be seen that although there are reversed torques introduced four times in each cycle, the resultant has a steady value, in this case being 80 per cent. of what it would be for the same pressure and current with unity power factor.

The armature reactions are also modified by the displacement of the phases. Whereas the reaction of one phase alone would be of a pulsating character, as was shown when dealing with the single-phase machine, the resultant of the four phases has a steady value.

This is owing to the phases following one another as the armature rotates, so that as the flux due to one phase is decreasing, that due to the next phase is increasing and so maintaining the resultant practically constant in value.

The poles of the armature flux are therefore stationary between the field poles, as in the c.c. generator, and the field flux is subjected to a steady distortion.

Lagging current in the armature, by causing the maximum to occur after the position of maximum pressure, shifts the poles of the armature flux forwards, weakening the field in a generator, and strengthening it in a motor. Leading current has the opposite effect.

The foregoing remarks on armature reaction apply equally to any polyphase machine. The reactions take place in the same relative directions as in the single-phase machine, but owing to the overlapping of the effects of the successive phases they do not pulsate, but have a uniform value throughout the cycle.

**Three-phase.**—In this machine the power will be divided equally between three phases, and in the example will be 333 watts per phase.

The phase pressure will be 0·866 of that between 180 degree tappings or 86·6 volts and the phase current $333 \div 86{\cdot}6$ or 3·8 amps.

The line current will be the resultant of the currents in two adjacent phases of the armature.

Now although the currents in adjacent phases have a displacement of 120 degrees, it must be remembered that any one tapping forms the trailing end of one phase and the leading end of the next.

Therefore as two phases in succession reach the position of maximum, their currents at those instants, while in the same direction in the armature, will be in opposite directions in the common tapping. That is, the two maxima in the tapping will occur in *opposite* directions with an interval of 120 degrees, which is equal to an added displacement of 180 degrees between maxima in the *same* direction.

The line current, then, is the resultant of the two phase currents of 3·8 amps., with a displacement of 120 plus 180 degrees, equal to a difference of 60 degrees. This resultant will have a value of 1·73 times the current in one phase, or 6·66 amps.

The pressure shown on switchboard voltmeters will be that between lines and the ammeters will show the line current. The phase current is obtained by multiplying the line current by 0·58, so that from the indications of the switchboard instruments the power in one phase will be equal to volts $\times$ amps. $\times$ 0·58.

The total power will therefore be equal to three times this, the expression simplifying into 1·73 $\times$ volts $\times$ amps. This is, of course, the apparent power, the real power being found by multiplying the foregoing by the power factor.

The torque on the armature will be the resultant of three single-phase torques displaced by 120 degrees, and will

have a constant value of 1·5 times the maximum of one phase alone.

**Six-phase.**—The 6-phase machine, as already pointed out, may be considered in three different ways, according to the manner in which the tappings are assumed to be grouped.

Considered as a 6-phase machine, the power will be divided between the phases, and in the example taken will be 166·7 watts per phase.

The phase pressure will be one-half that between 180 degree tappings or 50 volts, and the phase current 3·3 amps. The line current will be the resultant of two currents of 3·3 amps., in adjacent phases, with a displacement of 60 plus 180 degrees, equal to 120 degrees, and will also be 3·3 amps.

Considering the tappings as in two 3-phase groups, the watts per group will be 500, and the watts per phase 166·7. Dividing this by 86·6, the volts between 120 degree tappings, the result is 1·92, the amps., per phase.

The armature current is the resultant of two phase currents of 1·92 amps., one belonging to each of the groups, with a displacement of 60 degrees, equal to 3·3 amps., while the line current equals 1·73 times the amps., per phase, or 3·3 amps., once again.

Considering the machine as having three single phases connected between 180 degree tappings, the watts per phase will be 333, and this divided by the pressure, 100 volts, gives a line current of 3·3 amps., as before.

In each of the single phases the line current divides into the two paths through the winding so that the armature current per phase, taken singly, would be 1·67 amps., and this current would flow in opposite directions in each half of the winding.

Now taking any one conductor, it will be found that in

relation to two of the phases it is in one half of the winding, while to the remaining phase it is in the other half, having regard to the direction of current in the winding at the corresponding maxima of each of the phases, or at 120 degree intervals. The consequence is that the current in any part of the winding is the resultant of three currents with a phase difference of 60 degrees, this being the effect of reversing one of three with 120 degrees displacement. The resultant of three currents of 1·67 amps., with 60 degrees between them, is equal to twice the value of one of them, or 3·3 amps., as found by the other methods.

Thus it will be seen that from whatever point of view as to arrangement of phases the 6-phase machine is considered the result is the same. These particulars have been given to afford a guide to the reader in working out the pressures and currents for any system of connections used to supply rotary converters, the usual practice being to operate 6-phase machines from 3-phase systems by means of transformers which may be connected in various ways, all of which, however, give the same result at the converter.

Where ammeters are fitted to low-pressure switchboards for 6-phase converters these show the line current; voltmeters may show the pressure between tappings either 120 or 180 degrees apart, this depending on the system of connections used.

The torque of the machine will be the resultant of the torques of the six phases, and as these fall into three pairs, each of two phases whose torques coincide, the diagram will show three torque curves of a maximum height equal to twice that of one phase. The resultant of these three is 1·5 times the maximum of one of them, or three times that of one phase alone.

In rare cases converters may have tappings at 30 degrees, giving twelve phases. The advantage of using the larger

number of phases lies in the fact that for a given load the armature heating is less and more even the greater the number of phases. This, however, is largely offset by the increased cost of the extra sliprings and cables required, so such machines are very seldom met with.

# CHAPTER VII

## *ALTERNATORS IN PARALLEL*

**Synchronism.**—As with c.c. generators so with alternators, before connecting them in parallel it is necessary that the effective pressure in the circuit formed by the two armatures should be zero.

This condition is not fulfilled with alternators by merely having the pressures equal in value, but their alternations must be in step or in " synchronism " ; that is, the two frequencies must be exactly equal, and the pressures must have the correct relationship, so that at every instant they are in opposition to each other.

The resultant of the two pressures will then be zero in the local circuit, while an external circuit connected to the common terminals, or bus-bars, will be supplied from the two machines in parallel, the load being shared between them.

This condition is known as " phase opposition " or " synchronism."

If the two machines were connected together when 180 degrees from phase opposition, the pressure acting round the local circuit would be equal to the sum of the two machine pressures, while that acting on the external circuit would be zero.

This is known as " phase incidence," and in this condition no power will be transmitted to the external circuit.

The conditions necessary for the proper working of alternators in parallel and supplying energy to an external circuit are, equal frequencies and pressures, and phase opposition of the pressures.

An indication that these conditions have been attained may be given by lamps connected between the terminals of the main switch of the incoming alternator.

The lamps used must be capable of sustaining twice the pressure of either of the machines, as they will be subjected to this at phase incidence, and will glow with full brilliancy at such time.

At phase opposition the lamps will go out, showing zero pressure between the two machines, and the switch may be closed.

If the frequencies are unequal the lamps will glow and darken at a rate equal to the difference between the frequencies, the pressures being alternately in phase incidence and opposition.

A voltmeter may also be used instead of, or in conjunction with, lamps.

The foregoing is known as dark lamp synchronising; by using different connections for the lamps they may be made to indicate synchronism by glowing with full brilliance, this being called bright lamp synchronising.

The operation of paralleling alternators is described above in its simplest form; in the majority of instances instruments are used which show the moment of synchronism with greater accuracy than can be attained by the observation of lamps.

These instruments are known as synchroscopes, in which the action of the two pressures, that of the machine or machines already on load, and that of the incoming machine, rotates a pointer so as to show by the direction of its motion whether the incoming machine is too slow or too fast, and

also the condition of synchronism by its remaining stationary in a vertical position.

If the switch is inadvertently closed at the wrong time, the result is an interchange of power between the machines, greater or less according to the degree to which the pressures are out of phase, producing disturbing effects in the system besides the possibility of damage to apparatus.

In paralleling polyphase machines it is only necessary to know when one phase is in synchronism, as the relationship between any one phase and its neighbours is the same in each machine. For the same reason, when examining the behaviour of polyphase alternators in parallel by means of vector diagrams, as we shall be doing in the following section, only one vector for each machine is required.

**Synchronising Torque.**—The incoming machine having been switched in at phase opposition with the rest of the system, we have now to consider how this relation is maintained and the machines kept in step. A controlling force will be required which will counteract any tendency to fall out of step, and such a force can be supplied by the machines themselves, being brought into play by the change in the phase relations of the pressures with any departure from exact synchronism.

Consider two alternators $E_1$ and $E_2$ in parallel, their pressure vectors being lettered to correspond in Fig. 32. $E_1$ we will assume as being very large compared with $E_2$, so that the effect on the speed of $E_1$ of the load taken up or dropped by $E_2$ may be assumed negligible.

In diagram (*a*) the two pressures are exactly in opposition, the condition of synchronism and the instant of switching in $E_2$. The resultant is zero and there will be no current in the circuit formed by the two armatures.

If the supply of steam to the engine of $E_2$ is increased this machine will begin to speed up, and by so doing cause

its pressure to advance its position relatively to that of $E_1$.

That is, by completing each cycle in a slightly shorter time than $E_1$ its angle of lead from $E_1$ will be increased, or what is the same thing, its lag from $E_1$ will be reduced.

If the machine continued to run at the increased speed its pressure would, in course of time, advance in phase until half a cycle had been gained and phase incidence reached.

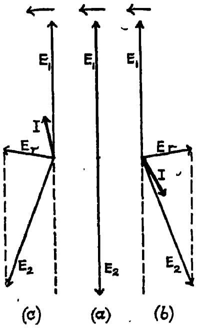


Fig. 32.

This is prevented, however, by the resultant pressure introduced by the change in phase displacement.

In (*b*) Fig. 32 $E_2$ has advanced by the angle shown and the resultant $E_r$ arises.

The circuit through the armatures of the machines is of comparatively low resistance and high inductance, and in consequence the current I produced by the resultant pressure will lag behind $E_r$ by a large angle as shown.

This current being displaced from $E_2$ by less than 90 degrees will produce a load torque on the armature of $E_2$ which will reduce the speed to its former value and check the further advance of the pressure wave. The machine thenceforward continues to run at its former speed, but with its pressure wave in advance of its previous position relative to that of $E_1$.

The reader should bear in mind that it is only by virtue of their exactly equal frequencies that the two pressures, as

represented by the vectors, are stationary with respect to each other. In this they may be compared to two men walking side by side at equal speeds. At every instant the position of one relative to the other will be the same and will remain unchanged while their speeds are unchanged.

If one man now begins to walk faster he will change his position relative to the other man by forging ahead, and if after accelerating he maintains an increased rate he will continue to change his position by continuing to gain. If, however, after accelerating for a short period he reduces speed once more to that of his companion, he will cease to change position, but will nevertheless maintain the lead which he gained during acceleration. Only by dropping below his companion's speed may he come back to his original relative position.

The same line of reasoning may be applied to the case of one man reducing his rate of walking and so dropping behind his companion.

To return to our alternators: if each machine is carrying part of an external load, the actual current in each armature will be the resultant of load current and the current due to the resultant pressure between the machines.

Advancing the vector $E_2$ is the equivalent of retarding $E_1$, the resultant arising in the same direction in each case. From this it will be seen that any departure from synchronism brings about an exchange of power between the two machines in such a way as to oppose such departure, the load on the leading machine being increased and that on the lagging machine reduced.

The larger the angle of displacement from phase opposition the larger will be the resultant, and the greater the synchronising power.

The load distribution between two or more alternators may be varied according to requirements by varying the

power input to the machines from their engines, and so changing the phase angles between their pressures.

**The Synchronous Motor.**—If one alternator has its power input reduced until it is just sufficient to overcome the various mechanical losses in the machine, such as friction, windage, etc., there will be no electrical output. A further reduction of the mechanical input will result in the speed dropping and the pressure wave being retarded until there is an input of electrical power from the rest of the system with which it is in parallel.

On cutting off the mechanical power entirely the whole of the work of maintaining the rotation will be taken up electrically, and the machine thus becomes a motor, the angle of lag of its pressure behind phase opposition with the supply pressure depending on the resistances to rotation which have to be overcome.

The conditions are shown in Fig. 32 (*c*), where $E_2$ is the pressure due to the machine now motoring. If a mechanical load is coupled to the motor the increased resistance to rotation will cause its pressure to lag still further, so increasing the resultant $E_r$ until sufficient power is taken from $E_1$ to meet the increased load.

Thus it appears that an alternator will operate either as generator or motor according to whether its pressure is made to lead or lag from opposition to that of other alternators it is connected with.

The speed of the motor will depend on the frequency, as it must run in synchronism with the generators, any attempt to depart from synchronism being automatically met by a change in the power input to the motor.

Increasing the load causes the pressure vector to swing backwards, increasing the resultant pressure and the power input; reducing the load allows the vector to swing forward with the opposite effect.

Owing to the necessity for running in step with the supply frequency, an alternator used in this way is called a synchronous motor, and is naturally a constant-speed machine.

If the supply frequency is divided by the number of pairs of poles in the field of a synchronous motor, this will give the number of revolutions per second of the machine at synchronous speed.

**Effect of Field Variation of A.C. Generator.**—When alternators are in parallel the effect of varying the field strength is to leave the load distribution practically unaltered, but to change the power factor.

This is best illustrated by a vector diagram as in Fig. 33 (*a*), where the two pressures are exactly in opposition. If $E_2$ is increased as shown by the broken line extension of its vector, there will no longer be exact balance of pressures in the local circuit, and the resultant $E_r$ equal to the excess of $E_2$ over $E_1$, will arise in phase with $E_2$. The current I, circulating between the two machines, will lag behind $E_r$ by a large angle for the reason stated earlier in this chapter, and if the machines are carrying load I will combine with the load current, and their resultant will be the actual current in the armatures.

As the current I leads in $E_1$ and lags in $E_2$ the power factors will be changed accordingly.

The field of $E_2$ will be weakened by the demagnetising component of I and the increase of field current offset to some extent thereby. That is to say, for a given increase of field current the rise in terminal pressure will be less when alternators are in parallel than when running alone.

The machine $E_1$ having a leading current will have its field strengthened, this tending also to reduce the disparity between the two pressures.

The power associated with I will be very small, being

just that required to make good the resistance losses in the local circuit, so that, as stated above, the principal effect of field variation is to change the power factors.

When the machines are running with less than 180 degrees between their pressures the same result attends the varying of the field strength of one of them. The resultant pressure will then be brought more nearly in phase

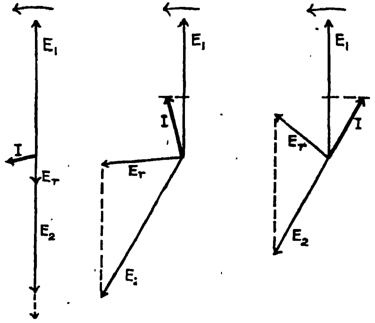



Fig. 33.

with the larger of the two machine pressures, and the current angle will be changed to correspond.

Stated briefly, if the terminal pressures of two alternators in parallel are unequal, there will be in the armature current of that having the greater pressure a lagging and demagnetising component, and in that having the smaller pressure a leading and magnetising component.

**Effect of Field Variation of Synchronous Motor.—**

The speed of the synchronous motor being determined by the frequency of the supply, variations in the field strength have no effect on it, but only alter the power factor. This is affected in the opposite sense to that of an a.c. generator, strengthening the field bringing about an advance in the current angle and weakening the field retarding it.

These relations are shown in (*b*) and (*c*) Fig. 33, where $E_2$ is the generated, or back, e.m.f. of the motor.

The phase angle of the current I is measured from the impressed pressure $E_1$, and is leading in (*b*) and lagging in (*c*), the weaker field in the latter case being indicated by the reduced value of $E_2$. The angle by which $E_2$ lags from opposition to $E_1$ depends on the mechanical resistance to rotation, that is, the load being driven, and as this has been assumed constant the actual power taken from the supply will be unaltered. This is shown by the dotted projection of I vertically on $E_1$ giving the same value of the power component of the current in each case, although the actual values of I, as will easily be seen by inspection, are unequal, the power factors being different.

Changes in the impressed pressure will also affect the power factor of the motor by altering the value and phase angle of the resultant pressure, and therefore of the current. In this case the effect is opposite to that of a corresponding variation of the back e.m.f., an increase of the impressed pressure retards the motor current and a decrease advances it, as a simple vector diagram will show.

As far as any one machine is concerned the best value of the field current is that which will give unity power factor, this entailing the minimum armature current for a given load.

The readiness with which the power factor of the synchronous motor can be controlled is often made use of in practice to compensate for other apparatus having an inherently low power factor. By operating such a motor

with a leading current, the lagging current from inductive loads can be neutralised, and the load on the generating plant kept much nearer unity power factor than would otherwise be possible.

Such applications as this, however, find but little vogue with rotary converters on account of the special nature of the heating effects caused in the armature of these machines by lagging or leading currents.

**Hunting and the Damper Winding.**—Hunting, to the occurrence of which all classes of synchronous machines may be subject in certain circumstances, may be briefly described as a series of periodic changes in the speed of rotation above and below that of synchronism.

With rapidly varying load, hunting, when once started, may continue and grow to such an extent as to involve risk of the machine losing synchronism. A motor which is hunting may set the generator doing likewise owing to the variations in the power taken varying the speed of the latter, or a motor may be set hunting by sudden changes in the power input caused by irregularities on the part of the engine driving the alternator.

In fact, with synchronous machines connected to the same system, anything which tends to change the phase relationships between their pressures will also tend to produce hunting to a greater or lesser extent, this depending on the relative sizes of the different machines and the magnitude of the disturbing cause.

Hunting arises from the fact that on account of its inertia, it is impossible for a rotating body to change its speed instantaneously.

As an example we may take the case of a sudden increase of load on a synchronous motor, and examine its effects on the vector diagram of the machine, which gives a picture of what is happening.

When the extra load comes on, the power input is for the moment inadequate, and the speed begins to fall, the vector moving backwards, and thus increasing the input.

The vector drops back until it reaches a position where the power input is sufficient for the load, and were it not for the inertia of the moving masses the speed would rise instantly to synchronism.

As it is, however, a certain time is taken for acceleration, during which as speed is still below normal the vector is still falling back, although at a decreasing rate, until when synchronous speed has been regained, the vector is farther back than is necessary; that is, the power input is greater than is required for the load.

The result is that the speed begins to rise above normal and the vector to move forwards again, until it reaches the correct position once more.

At this instant the armature is running too fast, and during the time taken to slow down the vector still moves forward until, when it comes to rest, at synchronous speed, it is in advance of its correct position, the power input is too small, and retardation of the armature begins. The whole cycle of events is then gone through again, the vector, as it were, oscillating about its correct position, and the current fluctuating in unison. Normally, hunting tends to die out after being started, but if fresh disturbances to the load take place, particularly if these occur at a frequency corresponding to what is known as the natural period of oscillation of the rotating mass, the hunting may be augmented to such a degree as to cause loss of synchronism.

Usually hunting can be detected by the changes in the speed being audible, while the ammeter will show the accompanying variation in the current.

As a result of hunting the armature current alternately lags and leads from its normal phase angle with the pressure,

and the armature flux will oscillate to and fro instead of remaining stationary.

Advantage is taken of this to introduce means for minimising hunting by the use of the damper winding, so called from its effect in damping out any variations from synchronous speed.

The damper consists of a series of copper bars embedded in slots in the pole faces so as to lie parallel to the armature conductors, and having all their ends connected together on each side, the end connections being carried across from one pole to the next so as to form a continuous ring right round the field system.

As the armature flux oscillates, the relative movement between it and the damper induces e.m.fs. in opposite directions in adjacent groups of bars, causing circulating currents, which by their interaction with the armature flux, impose torques on the armature which oppose the changes in speed.

When the speed falls and the flux swings backwards a motoring torque is produced, while when the speed rises the flux swings forwards and increases the load torque on the armature.

Any departure from synchronous speed then brings into play additional forces which oppose such change and tend to keep the speed constant, thereby reducing the tendency to hunt.

While trying over the relationships between the movement of the armature flux and the current and torque produced, it should be borne in mind when applying the right- and left-hand rules that the conductors, *i.e.* the damper bars, are stationary while the flux moves, which is equivalent to a movement of the conductors in the opposite direction.

# CHAPTER VIII

## *THE ROTARY CONVERTER*

**Double Current Generator.**—It has been shown that a machine having a lap connected armature winding can be made to give either continuous or alternating pressure at its terminals, according to the method of making connection between the armature and the external circuit.

As the fitting of a commutator for continuous pressure or tappings and sliprings for alternating pressure involves no modification of the winding itself, these may both be fitted to the same winding, when both kinds of pressure will be available. Such a machine when driven mechanically is known as a double current generator.

**Ratio between Continuous and Alternating Pressures.**—As both pressures are due to the same winding and magnetic field their values will bear some fixed relation to each other. The continuous pressure will be that between two neutral points in the winding, 180 degrees apart.

With tappings at 180 degrees the pressure between them will be greatest when they occupy these neutral positions, so that the maximum alternating pressure will equal the continuous pressure, and its virtual value will be equal to 0·707 of this.

The relation between the pressures available with different arrangements of tappings being known, we have

no difficulty in arriving at these values in terms of the continuous pressure.

For example, between tappings 120 degrees apart the pressure is 0·866 of that between 180 degree tappings; the virtual value of the latter being 0·707 of the continuous pressure the former will have a virtual value of 0·866 × 0·707, or 0·612 of the continuous pressure.

Proceeding on these lines the virtual values of the pressures between tappings in the various cases will be found to be as follows:

| Tappings. | Alternating pressure. |
|---|---|
| 180 degrees apart. | 0·707 of continuous pressure. |
| 120 ,, ,, | 0·612 ,, ,, |
| 90 ,, ,, | 0·5 ,, ,, |
| 60 ,, ,, | 0·354 ,, ,, |

These are theoretical values, based on a sine wave form, but in actual practice the values may be slightly higher, this depending on the wave form.

**Ratio between Continuous and Alternating Currents.**—For a given load the current at the commutator brushes will be equal to the watts divided by the volts.

For the same load on the alternating current side the current per slipring will depend on the number of sliprings, that is, the number of tappings per pair of poles.

To illustrate this we will consider the example taken in Chapter VI., a machine giving 100 volts virtual value between 180 degree tappings, and a load of 1000 watts.

The continuous pressure will be 1·41 times the above virtual value, so that the continuous current will be equal to 1000 ÷ 141, or 7·07 amps.

In the single-phase machine then, the slipring current will be 1000 ÷ 100 or 10 amps., which is 1·41 times the continuous current for the same load, assuming unity power factor.

Working out the current per slipring for different

numbers of rings in terms of the continuous current for equal watts, the following results will be obtained :—

| | | | | | |
|---|---|---|---|---|---|
| 2 rings, | current per ring | equals | 1·41 | times | continuous current. |
| 3 „ | „ | „ | 0·94 | „ | „ |
| 4 „ | „ | „ | 0·707 | „ | „ |
| 6 „ | „ | „ | 0·47 | „ | „ |

**Resultant Armature Currents.**—If the double-current machine is supplying both a c.c. and an a.c. load simultaneously, there will be a considerable difference in the armature current distribution as compared with what obtains when supplying solely c.c. or a.c. loads.

This is due to the fact that whereas the current from the commutator has a steady value in any conductor during the whole time it is passing from one brush to the next, the slipring current varies from zero to maximum and back again over successive periods of 180 degrees.

Furthermore, while the commutator current reverses in each conductor when it reaches the same point, the neutral of the field, the moment of reversal of the slipring current in any conductor depends on the position of the conductor relative to the tappings.

The pressure in any phase of the winding, and consequently the current (at unity power factor) is at zero when the tappings are on either side of the neutral points of the field.

This is the moment of reversal for that particular phase, and clearly, only those conductors midway between the tappings can be in the neutral points of the field. Therefore, only in these will the slipring current reverse at the same instant as the commutator current.

On the other hand, conductors adjacent to the tappings will be displaced from the neutral of the field by an amount depending on the spacing of the tappings.

The reversal of the slipring current in these will be

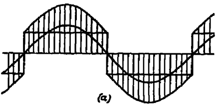
displaced from the commutator reversal by a similar amount.

For example, with tappings 60 degrees apart, a conductor situated immediately behind one of the tappings will pass through the neutral of the field 30 degrees before the reversal takes place in that phase.

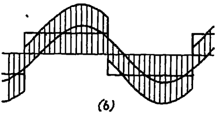
The commutator current will therefore reverse in that conductor 30 degrees before the slipring current, while for a conductor immediately in front of a tapping the converse will hold good, the commutator reversal lagging behind the slipring reversal by 30 degrees.

In general, conductors in the leading half of any phase will have the commutator reversal leading, and those in the trailing half the slipring reversal leading, the amount depending on their distance from the middle point of the phase.

The actual current in the conductors will be the resultant of the two load currents, and this will be different for each conductor owing to the varying displacement between the two reversals.



(a)



(b)

Fig. 34.

In Fig. 34 (*a*) the rectangular curve shows the commutator current, reversing at intervals of 180 degrees.

The sine wave of slipring current is in phase with the other, thus referring to a conductor midway between tappings, while the resultant of the two is shown by the shaded line.

In (*b*) are shown the corresponding curves for a conductor

immediately in rear of one of the tappings, which are assumed as 60 degrees apart.

The sine wave therefore lags behind the rectangular wave by 30 degrees, and the effect of this on the resultant should be noted.

For short periods the two currents are in opposite directions so that they cancel each other to a certain extent, thus reducing the effective value of the resultant. This means that the heating in conductors situated adjacent to the tappings will be less than in those midway between them.

In the foregoing the a.c. and c.c. loads have been assumed to be equal, and the power factor unity, any lag or lead of the current having the effect of causing the slip-ring current reversal to take place later or earlier accordingly.

It is not necessary to deal further with the behaviour of the machine as double current generator, the object being to lead up to its operation as rotary converter.

**The Rotary Converter.**—If the double-current machine is running in parallel with other plant on both c.c and a.c. sides, and the power of the driving agent is cut off, the machine will continue to run as a motor, and under certain conditions of field excitation will take power equally from both sides to maintain the rotation.

The speed, of course, will be that of synchronism.

If, while running under these conditions, the field is slightly weakened the internal pressure will be reduced, and a larger current will flow on the c.c. side. This will tend to cause an increase in speed.

On the a.c. side, however, the pressure which has been lagging slightly from phase opposition with the supply, in order to allow of the power input necessary to assist in driving the machine, will have its lag reduced by any increase in speed.

In consequence the power taken from the a.c. side will be reduced, the total power required, which is still the same, being now supplied in larger proportion from the c.c side.

By adjusting the field excitation suitably, the whole of the power may be taken from the c.c side, the pressure at the sliprings being then in exact opposition to that of the supply and no power taken therefrom. A further decrease in the field strength will cause the slipring pressure to lead from phase opposition and power will be delivered to the a.c. system, a corresponding amount being taken from the c.c. system by the larger current due to the weakened field.

On the other hand, with the machine motoring equally from either side, if the field is strengthened the increase in the internal pressure reduces the current on the c.c. side, the slipring pressure drops back still further, and more power is taken from the a.c. side. If the field is increased sufficiently, power may be transferred from the a.c. to the c.c. system, and it is in its application to such transference of power from one system to another that the machine is termed a rotary converter.

The most common use of these machines is to convert from a.c. to c.c., the opposite conversion being known as "inverted" running.

**Armature Current in Rotary Converter.**—As in the double current generator, the current in the armature conductors is the resultant of the commutator and slipring currents, with the important difference that these are in general in opposite directions.

This has the effect of very materially reducing the actual current in the conductors from what it would be were the machine giving a similar output as either plain c.c. or a.c. generator.

The current in the conductors also varies with regard to

their distance from the tappings, but in this case those midway between the tappings carry the smallest current.

This arises from the fact that, the reversal of the two currents occurring simultaneously in these conductors, their direction is always opposite to each other, thus giving the most complete neutralisation.

In conductors nearer the tappings, however, the two currents are displaced to a greater or lesser degree from exact opposition, so that during certain periods they are in the same direction, or cumulative.

The amount of the displacement between the two reversals is limited, at unity power factor, to one-half the distance between tappings. With the smaller number of phases the amount of this displacement, in the conductors adjacent to the tappings, is greater than with tappings closer together, so that in the former the periods when the two currents are in the same direction are longer ; in addition to this the current per phase is greater for a given load, the fewer the phases. The larger the number of phases the machine is arranged for, therefore, the smaller and more uniform is the armature heating.

These points are illustrated in Fig. 35. which shows the commutator, slipring, and resultant currents for a conductor, in (*a*) midway between tappings, and in (*b*) next to a tapping, in a single-phase, and a 6-phase machine.

The much smaller resultant in the 6-phase machine will be readily noticed.

On account of the low R.M.S. value of the armature current, polyphase converters may be made smaller than plain c.c. generators for the same output. Conversely. a polyphase converter, operated as such, will give a greater output for a given heating than if operated as a c.c. generator. Outputs for equal heating for converters of different numbers of phases, as compared with the same

machine operated as c.c. generator, are as follows: 3-phase, 1·34; 2-phase (4-phase), 1·64; 6-phase, 1·97 of c.c. rating. For a single-phase converter the relative output for equal heating is only 0·85 of the plain c.c. rating.

**Resultant Torque.**—Referring to Fig. 35, it will be observed that the resultant current reverses several times during 360 degrees, at some parts of the cycle being in the generated direction and at others in opposition.

This indicates reversals of torque, the final result being

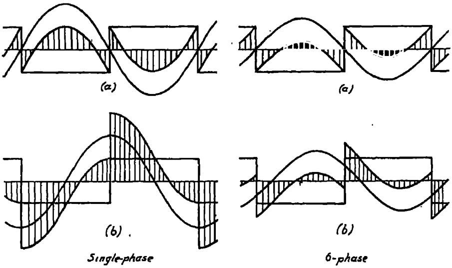



Fig. 35.

that, neglecting losses, the sums of the opposing torques are equal, which means that the whole of the power input is transformed electrically, no mechanical power being transmitted to the shaft.

In actual practice, owing to the unavoidable losses, such as friction and windage, the power necessary to supply these is converted into mechanical form and transmitted through the structure to the various points where these losses occur, with a corresponding reduction of electrical power output for a given input.

In Fig. 35 these losses have been ignored and the input and output assumed equal.

**Effect of Lead and Lag on Armature Current.**—When the power factor is less than unity the armature heating is increased, particularly in those conductors adjacent to the tappings, this effect being due, not so much to the increased current for a given load, as to the increase in the displacement between the commutator and slipring reversals in certain conductors.

For example, in a 6-phase converter, at unity power factor the a.c. reversal in a conductor situated immediately behind one of the tappings will take place nearly 30 degrees later than the commutator reversal; whereas with the slipring current lagging behind the pressure this displacement will be increased by the amount of such lag, with consequent increase of the R.M.S. value of the resultant.

Conductors situated in front of a tapping will have the displacement between the two reversals (a.c. reversal preceding the other in this case) decreased by lagging current, thus reducing the R.M.S. value of the resultant in spite of the increase of the slipring current due to the lower power factor.

In Fig. 36 is shown the effect of a lag of 30 degrees in the current for a conductor in the same position as that in Fig. 35 ($b$). The 30 degree displacement between the two reversals has been increased by a further 30 degrees owing to the lagging current, the effect on the resultant being very noticeable.

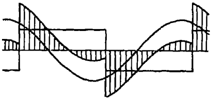


Fig. 36.

With lagging current, then, the resultant current is increased in conductors behind the tappings and decreased

in those in front of the tappings in the direction of rotation, while the conductors having the minimum current are no longer those at the middle point of the phase, but those to the rear of this position.

With leading current the effects are the opposite of those outlined above, the displacements between the two reversals being affected in the contrary direction.

**Commutation.**—As each armature coil arrives at the neutral points there is a change in the value of the current in it equal to twice the value of the continuous current.

In the c.c. generator this consists of a change from full value in one direction to an equal value in the other direction.

In the rotary converter, however, this is not always the case, the change may be from one value in a given direction to a larger or smaller value in the other, or even from one value to another, greater or less without reversal, this depending on the position of the coil with reference to the tapping points.

Only in those coils in which the slipring reversal coincides with the commutator reversal is the change one between equal values in opposite directions.

These points may be seen illustrated in Figs. 35 and 36, but it will be observed, nevertheless, that the actual change in the current is always equal to twice the commutator current, as stated above.

Commutating poles in rotary converters have practically only one duty to fulfil, that of changing the value of the current in the coil.

In the c.c. generator, as was pointed out when dealing with interpoles, these have to be of sufficient strength to divert the armature cross flux from that part of the armature wherein are the coils undergoing commutation,

as well as to provide a flux in the proper direction to effect reversal of the current in the coils.

In the rotary converter the cross flux is the resultant of two opposing effects, so that there is more or less neutralisation of each other, the actual degree of this depending on the relative values of the currents on each side of the machine.

The worst case is that of the single-phase machine, where the armature reaction due to the alternating current is intermittent, while that due to the commutator current is constant so that when the former is at zero the latter exists alone, while when the former is at maximum the reaction is reversed owing to the greater value of the alternating current for a given load.

The commutating flux, which has to be strong enough to maintain a reversing field in the armature against the cross flux at a.c. zero, will be augmented by the reversed cross flux at a.c. maximum, this variation in the strength of the interpoles rendering commutation very unsatisfactory.

On the other hand, the cross flux in a polyphase armature is constant in value for a given load, so that in the polyphase converter, the two reactions, motoring and generating, being constant and in opposite directions will neutralise each other.

Actually, of course, the two reactions do not exist separately, but in many ways it is convenient to consider them thus, and by comparing them to arrive at an understanding of their combined effect.

If the slipring current is lagging or leading from the pressure the result will be the same as in the polyphase motor, a strengthening or weakening of the field.

Under these conditions the motoring cross flux, considered separately, may be looked on as consisting of two

components, one tending to distort the field, but always proportional to the load and balanced by the generating cross flux, the other one situated 90 degrees from the former and therefore opposite the field poles, reducing or increasing the main flux as the case may be.

When hunting occurs, the motoring armature flux may be considered as oscillating backwards and forwards about its normal position, as the current alternately leads and lags.

This is accompanied by variations in the power input, and the load being supposed constant, energy is alternately stored in and withdrawn from the rotating mass of the armature as the speed fluctuates.

This means that the power component of the driving current is not always equal to the load on the machine, so that the balance between the armature reactions is being subjected to periodic disturbance, resulting in a swaying to and fro of the flux in the commutating region. This in its turn tends to cause sparking at the commutator brushes.

**Pressure Ripple.**—Among the phenomena which occur during the operation of rotary converters is that of a periodic fluctuation of the pressure generated, known as ripple. This may be caused by commutation, or by the effect on the flux of the slots for the armature and damper windings. Ripple produces undesirable effects by mutual induction in telephone circuits, where these lie adjacent and parallel to supply lines connected to either the a.c. or c.c. sides of the converter, and particularly is this so when the frequency of the ripple lies within the range of frequencies employed in human speech. Ripple may be caused by the wave form of the e.m.f. induced in the armature conductors, and the simplest case of this may be briefly explained as follows. In any armature conductor the e.m.f. rises from zero to maximum and falls back to

zero during the passage of the conductor from one neutral point of the field to the next, and the rate at which these changes occur, in the rotary converter with suitably designed flux distribution, follows a sine law. At any instant, there are a certain number of conductors in series between two adjacent sets of commutator brushes, and the e.m.fs. in these will all be at different parts of their respective half sine waves: the total pressure between brushes will therefore be the sum of these different e.m.fs.

If there were an infinite number of conductors there would be one in every possible position at every instant, and the sum of their e.m.fs. would be constant. Actually, the number is limited and the conductors therefore have a space interval, and this is further increased by the grouping of the conductors in slots. The result is that the sum of the e.m.fs. induced varies according to whether there are conductors in the position of maximum induction or not, at the instant taken.

For example, we may consider the position when the point of maximum induction lies midway between two conductors, and then assume that the armature moves forward the distance of one conductor space. All the conductors on one side of the centre move towards the denser part of the flux and their e.m.fs. increase, while all those on the other side of the centre move towards the weaker part of the flux, and their e.m.fs. decrease. The changes in the e.m.fs. induced in these conductors will therefore balance each other. The conductor which passes through the position of maximum induction, however, will have a rise and fall of the e.m.f. induced which is not neutralised by a corresponding change in any other conductor, and this appears at the commutator brushes in the form of a ripple, with a frequency equal to the number of conductors passing a given point per second.

The actual form of this ripple is complicated by the grouping of the conductors in slots, and also by the distance apart of conductors forming one turn of the winding; as stated above, only the simplest case has been considered here.

In ordinary c.c. generators this ripple is eliminated by designing the field so that the e.m.f. induced is the same in conductors in any part of the flux, that is, the wave form is flat topped. In the rotary converter this cannot be done on account of the sine wave form required, so the effect of the ripple is minimised by making it of as high a frequency as is permissible, consistent with other requirements of the design. This is brought about by using a large number of conductors per pair of poles, the amount of the ripple being reduced, and its frequency increased thereby. This practice is advantageous in another respect also, in that it reduces the pressure between adjacent commutator bars, and thus lessens the liability to flashing over on the commutator.

The variation in the number of coils short-circuited by the brushes may also cause a ripple. For instance, in Figs. 7 and 8, in the position shown, one coil is short-circuited, whereas a short time earlier or later the brush will be resting on parts of three bars, and two coils will be cut out: the number of active conductors between brushes therefore varies by two. In the rotary converter the coils thus added or subtracted are in the weakest part of the flux, and their influence is still further reduced by having a large number of conductors per pair of poles, as the ratio of two conductors to the total number is thus made smaller.

Ripple due to armature slots is caused by bunching of the flux, which takes place as a result of the higher reluctance of the airgap over the slots as compared with that over the teeth between them. When a tooth is

passing out from under a field pole it carries this bunched flux with it a certain distance, until the reluctance of the path becomes too high and the flux, as it were, snaps back to the next following tooth. Similarly, when a tooth is approaching a pole, the flux may be considered as springing out across the preceding slot to meet the tooth. The result of each of these is that there is a momentary increase of the e.m.f. in the conductors in these slots, producing a ripple with a frequency equal to the number of teeth passing one pole in one second. The armature slots should be of such a number as will produce a ripple with a frequency high enough to cause no interference with neighbouring circuits.

Damper bars, as a rule, are not placed in open slots in the pole faces, but are passed through holes in the pole tips from one side to the other. Being composed of non-magnetic material, their presence increases the reluctance of those parts of the pole tips in which they lie, causing the flux to bunch in the spaces between the bars. Ripple due to this may be neutralised by either spacing the damper bars at a distance of one and a half times the armature slot spacing apart, or placing the bars in adjacent poles so that when armature slots lie under the bars in one pole, armature teeth are under bars in the next pole. Two ripples in opposition are then produced, which balance each other.

**Uneven Wear of Sliprings.**—A good deal of trouble is often caused by uneven wear of sliprings, hollows being formed in the rings, and burnt patches, due to sparking, appearing. These hollows are found to correspond in number to the pairs of poles in the field, and are due to the fact that, when the current is flowing from the ring to the brushes, the wear is greater than when it is in the opposite direction. The amount of inequality in the wear depends on the length of time that any part of the ring is in contact

with the brushes, that is, on the extent of the arc covered by the brushes.

If this arc is of the same number of geometrical degrees as is contained in two pole pitches, each part of the ring will make contact during the time taken for one cycle, although, of course, only certain points on the ring will begin and end their period of contact with the beginning and ending of the cycle. Other parts will come under the brushes earlier or later in the cycle, and will leave them correspondingly later, but the total result will be that every part of the slipring will carry current for an equal time in each direction. The wear will therefore be uniform, so far as it is affected by direction of current.

If the brushes make contact over an arc equivalent to less than two pole pitches, only certain points on the ring, equal in number to the pairs of poles, will have the wear equalised by being in contact with the brushes during equal parts of successive half-cycles. At all other parts the rings will carry current for a longer period in one direction than in the other, and the wear will vary accordingly.

There are many machines in service in which the slipring brushes cover too small an arc, necessitating frequent grinding or turning down of the rings.

# CHAPTER IX

## *PRESSURE CONTROL*

**By Simple Field Regulation.**—The variation of the continuous pressure of a rotary converter is not the straightforward matter that it is with the c.c. generator, on account of the effect which field regulation has on the a.c. characteristics of the machine.

The vector diagram shows that varying the excitation of a synchronous motor changes the phase angle of the current, and it is this alteration of the power factor, and the armature reaction effects arising therefrom, which constitute the problem with the rotary converter.

When the converter is running with a lagging current, the actual field flux will not be that due to the exciting current in the field coils alone, but will be composed of this plus the magnetising effect of the armature reaction, and the generated pressure will correspond.

If an attempt is made to increase the generated pressure by increasing the field current, the lag of the armature current is reduced and the magnetising reaction decreases, thus tending to counteract the increase of the field current.

On the other hand, reducing the exciting current increases the lag and therefore also the armature magnetising effect.

Similarly, when the current is leading, increasing the field current causes greater lead and increases the de-

magnetising reaction, while reducing the exciting current has the opposite effect.

There is thus a differential action produced whereby any change in the field excitation causes an opposing change in the armature reaction.

Simple regulation of the field current, therefore, is of very little use for varying the continuous pressure generated, unless something is done to prevent the phase angle of the current on the a.c. side being affected, and several methods are in use for this purpose.

In general, such methods have for their object the varying of the impressed pressure, and a glance at a vector diagram will show that if this is done in correct proportion to the change in generated pressure no change in power factor will occur.

Control of the continuous pressure is thus obtained over a range varying with the method used, and while in some cases the power factor varies to a certain extent, in others it may be maintained constant throughout the whole range and at all loads.

The several methods used are as follows:

Varying the supply pressure at alternator terminals.

Changing tappings at transformer.

Series reactance.

Induction regulator.

Synchronous booster.

**Varying Alternator Pressure.**—In comparatively few instances is it possible to vary the pressure at the alternator in accordance with the requirements of the converter, but where it can be done, as when the whole output of an alternator is converted to c.c., no auxiliary apparatus is necessary beyond the field regulators of the two machines, while compounding may be obtained by means of an

automatic regulator for the alternator and a series winding on the converter field.

In the majority of cases, however, converters are operated as part of the general load on an a.c. system, so that variation of the supply pressure at its source is impracticable.

The methods employed in such cases involve the use of apparatus which is a modification of, or additional to, the requirements for conversion alone, and in deciding which to adopt, regard has to be paid to the range of pressure variation required, as well as to the cost of the necessary apparatus.

**Changing Transformer Tappings.** — It sometimes occurs that converters are required to give two distinct ranges of pressure at different times, as for instance, 440 volts for public supply and 550 volts for tramway work. As in most cases these machines are used with transformers which reduce a high pressure supply to a value suitable for the continuous pressure required, such conditions are most easily met by altering the connections to the transformers so as to get the two desired values for the slipring pressures.

Facilities can be embodied in the construction of the transformers, whereby the change may be made quickly and simply at the time of changing from one c.c. system to the other, although it is usually necessary to shut the machine down for the purpose.

If a minor range of pressure variation is required in addition this can be provided for by one of the other methods of control, which by itself would not be sufficient for such a large step as that mentioned above.

**Field Regulation with Series Reactance.**— Where the range required is comparatively small, that known as the reactance method of control is usually adopted.

In this, use is made of the e.m.f. of self-induction in suitable reactance coils in series with the supply circuit to effect a variation of the pressure applied to the sliprings.

This is done by varying the excitation of the converter and thus changing the phase angle of the current, leading current causing the resultant of the supply and reactive pressures to increase, and lagging current having the opposite effect. A little consideration will show that if the current were made to lag by 90 degrees, the reactive pressure, lagging a further 90 degrees would be in exact opposition to the supply pressure, while a current leading by 90 degrees would produce a reactive pressure in phase with the supply. In actual practice, of course, such extremes cannot be even approached on account of the effect of the low power factor on the armature heating, and the restriction of permissible output thereby involved. Nevertheless, a range of pressure at the sliprings up to about 12 per cent. of the mean value can be obtained, while still keeping the power factor within practicable limits.

The effect of the reactive pressure can best be studied by vector diagrams. In Fig. 37 (*a*) I is the armature current leading by a small angle on $E_s$, the pressure at the sliprings. $E_s$ is the resultant of $E_a$ the supply pressure, and the reactive pressure $E_x$ which is induced in the reactances by the current, and consequently lags therefrom by 90 degrees. $E_s$ will be seen to be equal to $E_a$.

With load remaining constant, strengthening the field causes the current to lead still further, and the resultant increases, as in (*b*), while a reduction of the field strength brings about the conditions shown in (*c*), the current lagging and $E_s$ being reduced, $E_a$ remaining constant throughout. Thus the generated and impressed pressures are varied by field regulation, the effect on the power factor being less,

and on the generated pressure greater, than it would be without the reactance.

At any load, for a given commutator pressure the power factor is fixed, as one of these cannot be altered without changing the other, while from no load to full load the pressure and power factor will remain practically constant. if the excitation and supply pressure are kept constant. There may, however, be an increasing drop in the supply pressure with increasing load, in which case, in order that

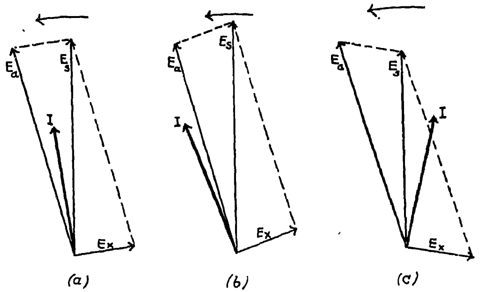



Fig. 37.

the slipring pressure may be kept constant, it will have to rise above that of the supply by an amount equal to the drop in the latter. Further than this, there is the question of compounding required at the c.c. end to allow for the pressure drop in feeders, etc., so that the slipring pressure may be required to be higher at full load than at no load.

If the changes of load are few or gradual this may be done by hand regulation of the converter field, but where rapidly fluctuating loads have to be dealt with automatic

action is necessary, and is obtained by fitting a series winding to the field magnets. By this means the field is strengthened with increasing loads and the generated and slipring pressures raised accordingly, the series field turns and the reactance being designed to give the required degree of compounding.

When compounded thus the current gradually advances in phase from no load to full load, and in order that the most favourable conditions may be obtained, the design is usually arranged for a low lagging power factor at no load, improving to unity or thereabouts at full load. At the smaller loads, even with the low power factor, the total current will be comparatively small and the heating unimportant.

Fig. 37 shows that as the slipring pressure always lags behind the supply pressure, the power factors of converter and supply will be different. For example, in (*a*) the former is leading and the latter lagging, in (*b*) the current leads in both but by different angles, while in (*c*) it lags by a different angle in each.

With the current leading the supply pressure, the power factor of the converter will be lower than that of the supply, and this becomes of importance when the question of the full load power factor of the machine is considered.

If this is too low and leading the supply, while no doubt beneficial in correcting to some extent low lagging power factor in the system, yet the converter itself has to be made larger, and therefore more costly, on account of the heavier current it has to carry.

On the other hand, by having the reactance designed to give unity power factor at the converter on full load, the energy is taken from the supply at a low lagging power factor. As a compromise, a slightly leading current at full load is often specified, and by this means the power

factor of the supply is kept as high as possible without unduly lowering that of the converter.

The wider the range of pressure control required, the greater will be the variation of the power factor necessary to obtain this, which results in a larger machine for a given rating. On this account reactance control is restricted, as mentioned above, to a range of about 12 per cent. total variation, all of which, however, may not be available at the commutator owing to the amount required to compensate for pressure drop on the supply side.

The reactance in the supply circuit may be provided either by using transformers in which the normal amount has been increased by special design to the value required, or by separate reactance coils in addition to standard transformers.

**Induction Regulator.**—In this method the pressure applied to the sliprings is varied by a piece of apparatus called an induction regulator or booster. This is a special type of transformer, which in its simplest form has two coils, the primary and the secondary, so arranged on a laminated iron core that the flux set up by a current in one coil links with the other.

When the primary is traversed by an alternating current an alternating flux is set up in the core, and this produces an alternating e.m.f. in the secondary coil.

The magnetising current in the primary lags by 90 degrees from the pressure, and the flux will do likewise.

The secondary e.m.f., depending as it does on the rate of change of the flux, will lag by a further 90 degrees, and so will be in the opposite direction to the primary e.m.f. round the core at any instant.

The value of the pressure available at the terminals of the secondary will be proportional to the number of turns in the coil, so that by having a secondary with more or

fewer turns than the primary, a pressure greater or less than the primary pressure will be obtained.

For further details of the action of the transformer the reader is referred to Chapter XIV.

Varying the number of secondary turns is not a practicable method of regulating the secondary pressure of an induction regulator on account of its coarseness, moving as it must do in steps instead of by even graduation, while the fact that regulation is required when under load introduces further objections. The two windings are therefore so arranged that their relative positions may be changed, so as to vary the flux linking with the secondary, and thus to vary the secondary pressure.

This is done by placing one winding in slots in the surface of a cylindrical core somewhat like an armature, and the other winding in corresponding slots in the inner surface of a hollow cylindrical core which surrounds the former, leaving a very narrow airgap.

The inner core is called the rotor and is capable of rotation through a certain distance by suitable gearing, usually operated by hand, while the outer core is the stator, and as its name implies, is fixed.

Either of them may carry the primary or secondary winding. By placing the rotor so that the axis of its windings coincides with that of the stator winding, the same flux links with both and the secondary pressure will have its greatest value, while its direction in the external circuit will have a definite relation to the direction of the pressure in the primary. If the rotor is moved through 180 degrees, the total flux linkage and secondary pressure will again be a maximum, but its direction in the external circuit will be opposite to that formerly existing relatively to the primary pressure.

Midway between these two extreme positions the two

windings will be at right angles, and the flux linking with the secondary zero; the secondary pressure will therefore also be zero, and may be built up gradually in either direction relatively to the primary by moving the rotor one way or the other, so increasing the flux linkage with the secondary.

The arrangement of a single phase induction regulator is shown diagrammatically in Fig. 38. The primary is connected across the supply, and the secondary in series with the leads to the converter sliprings.

The arrows show the direction of the pressures in the circuits at corresponding instants, and it will be readily

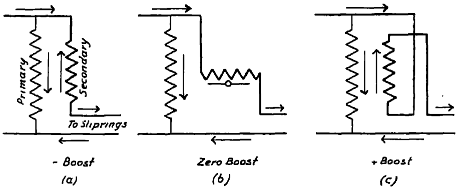



Fig. 38.

seen how the secondary pressure may be used to oppose (as in (*a*)), or assist (as in (*c*)) the pressure to the converter by changing the position of the movable winding, the secondary in this case.

The upper limit of pressure variation will be the normal supply pressure plus boost, and the lower limit normal minus boost.

With polyphase supply the action is somewhat different, on account of the resultant effect of the several alternating fluxes with a phase displacement.

If the primary coils of a 3-phase booster are arranged on the core with the proper space interval of 120 geometrical

degrees between them, each will produce a flux, the three fluxes differing in time by one-third of a cycle, or 120 electrical degrees, and being displaced round the core by the same amount geometrically. The effect of this is to produce a resultant flux which has a constant maximum value and rotates round the core, making one revolution in the time of one cycle of the supply.

This flux will link with the secondary windings, and as these are stationary and similarly spaced at 120 geometrical degrees, the flux linkage with each secondary phase will alternate and induce secondary e.m.fs. with the correct phase displacement of 120 degrees.

Now the value of the secondary pressures will be entirely unaffected by the relative positions of primary and secondary phases, as the flux will sweep over every part of the secondary windings during each revolution. What will be altered, however, by shifting the rotor, is the phase angle between a given primary phase and any of the secondaries.

Take, for example, a 3-phase booster having the primary windings on the rotor, and the secondary phases connected in series with the supply to a rotary converter, the primaries being energised from the same source of supply.

With a certain position of the rotor the pressure induced in the secondaries will be in phase with the pressure in the converter circuit, and this will hold good for all three phases, as the supply pressures reach maximum in successive phases at intervals of 120 degrees, and so likewise do the boost pressures. The pressure applied to the converter slip-rings will then be equal to that of the supply, plus the secondary pressure of the regulator. If the rotor is moved, say 30 degrees, in the direction of the flux rotation, the phase of the boost pressure is advanced by that amount with respect to the direction of supply pressure in the secondary

windings. That is, a given pole of the flux will now reach any secondary phase 30 degrees earlier, and the secondary pressure will lead the supply.

If the rotor is advanced 180 degrees from the first position the primary flux will gain half a cycle on the rotation of supply pressures in the secondary, and the boost pressure will be in opposition to the supply.

The pressure at the converter sliprings, therefore, will at any time be the resultant of the supply and boost pressures, the angle between these being capable of variation between incidence and opposition, and the resultant accordingly having a range from supply minus boost to supply plus boost.

The vector diagram of these pressures is given in Fig. 39, $E_s$ being the supply pressure, and $E_b$ the pressure given by the secondary of the booster.

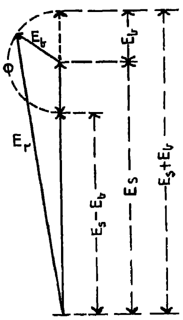


Fig. 39.

The end of the resultant pressure vector $E_r$ will lie somewhere on the broken semicircle according to the phase angle between supply and boost, and it is readily seen how $E_r$ becomes larger or smaller than $E_s$ with a constant value of $E_b$ by a change in the phase angle. When the angle is such that $E_b$ lies on the point marked O, $E_r$ is equal to $E_s$, that is, the effective boost is zero.

It will be observed that only at full boost in either direction is $E_r$ in phase with $E_s$. With any other value of the effective boost these two are out of phase, and the power factor of the converter will differ from that of the supply.

Adjustment of the impressed pressure by the induction regulator and of the field strength of the converter enables the commutator pressure and power factor to be varied independently, a very close regulation of either over a wide range being possible. A disadvantage is that the induction regulator itself is a comparatively expensive piece of apparatus, and its use is only justified when the range of pressure control desired cannot be efficiently met by other methods. A diagram of the connections for a 3-phase regulator is given in Fig. 40.

Although the diagrams in Figs. 38 and 40 indicate

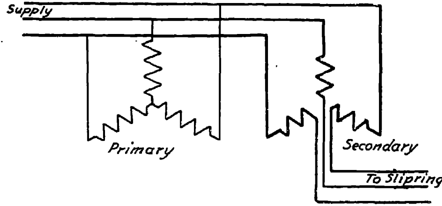



Fig. 40.

boosters having a two-pole field, these machines may be made multipolar by winding both parts with the requisite number of coils and connecting them in the proper manner.

With a multipolar booster the rotor has, of course, only to be moved through 180 electrical degrees, or one pole pitch, to obtain the extreme range of boost pressure.

**Synchronous Booster.**—The synchronous booster is a small alternator which has its armature windings connected in series with the supply to the a.c. side of the converter.

In machines of large output the booster armature may be stationary, the field magnets being mounted on the

converter shaft and the exciting current supplied through sliprings. The armature coils are connected on one side to the a.c. supply, and on the other to the converter slipring brushes.

It is more usual, however, for the booster field magnets to be stationary, and the armature to rotate with the converter shaft. In this case the armature coils are connected in the leads from the sliprings to the tappings of the converter armature.

The pressure induced in the booster armature windings can thus be added to, or subtracted from the supply pressure, according to the direction of the booster field excitation. The booster field must obviously have the same number of poles as the converter field, as both armatures run at the same speed.

Various arrangements of field excitation are used, such as shunt from the c.c. side of the converter, series, or compound.

Booster field shunt circuits are provided with a regulator and in some cases a reversing switch, so that the boost pressure may be varied or reversed as required. For hand regulation the converter and booster field circuits may be entirely separate, or, in addition to the shunt winding on the converter poles, there may be an auxiliary winding connected in series with the booster field circuit, so that the boost and converter pressures are varied simultaneously.

For compounding, the booster field may have a series winding carrying the c.c. load current, so as to vary the impressed pressure with the load, in which case hand regulation of the converter field is required in addition. Alternatively, both field systems may have a compound winding so that both pressures are varied automatically with the load. By hand regulation of both fields the

commutator pressure may be varied at will and the power factor adjusted to any value.

The practicable range of pressure control with the synchronous booster is about 12½ per cent. above or below normal, or 25 per cent. total, limiting factors being the effect which boosting has upon commutation and armature heating.

When the booster is in operation it is being driven by the converter, which transforms part of the electrical input into mechanical form to meet the load imposed by the booster. The power required to drive the booster is equal to the work done in raising the pressure to the converter, so that what the booster receives in mechanical form from the converter is given back to it electrically. The input to the converter is therefore equal to the c.c. load plus the watts added by the booster, the latter quantity providing the motoring torque required to drive the booster.

The foregoing applies to the conditions when the slipring pressure is being raised, *i.e.* the boost is positive.

When the boost is against the impressed pressure the conditions are reversed, the pressure induced by the booster being in opposition to the current, and the booster therefore operating as a motor. The result of this is that power is transmitted mechanically from the booster to the converter, where it is again transformed and reappears in electrical form at the commutator as part of the c.c. output.

The electrical input to the converter is thus reduced by the amount transformed into mechanical energy by the booster.

To sum up, when the boost is positive the converter input is wholly electrical and the output partly electrical and partly mechanical, while when the boost is negative

the converter input is partly mechanical and partly electrical and its output wholly electrical. In addition to its duty as rotary converter the machine may be considered to operate as motor in the former case and as c.c. generator in the latter.

The resultant armature current therefore has a preponderating motoring or generating effect, and a cross flux arises which tends to distort the main field flux in one direction or the other, according to which of the above-mentioned conditions exists.

The effect of this is to vary the flux in the commutating region and so cause sparking at the brushes. This may be to some extent overcome by providing the interpoles with an auxiliary winding which is connected in series with the booster field circuit, its effect assisting or opposing that of the main interpole winding in varying degrees, according to the direction and amount of the boost.

When boosting is positive the interpoles, which are always of the same sign as the next poles ahead, have added to them the cross m.m.f. of the armature, which when the electrical input exceeds the electrical output, will produce poles in the armature of the same sign as the field poles behind them. The interpoles and their associated armature poles are therefore of opposite sign and the flux is increased.

The auxiliary winding is connected in such a manner as to reduce the interpole m.m.f. when the booster field is excited in the direction for positive boosting, the effect of the armature m.m.f. being thereby neutralised. When the booster field current is reversed for negative boosting the auxiliary excitation of the interpoles is reversed also and therefore assists the main winding, so compensating for the opposing effect of the armature m.m.f. which arises from the excess of electrical output over input.

The want of balance between electrical input and output when boosting also increases the R.M.S. value of the resultant armature current, with consequent increase of the armature heating for a given output with boost.

The position of the booster field poles with reference to those of the converter is of importance, as in order to get the maximum effect of the boost pressure it is necessary that it should always be in phase with the impressed pressure.

When the load on the converter is increased the armature drops slightly behind its former position relative to the supply pressure, as was explained when dealing with the synchronous motor.

This means that the armature tappings reach the position of maximum pressure later than the occurrence of the impressed pressure maximum, by an increasing degree as the load becomes greater.

The booster armature being rigidly coupled to the converter is affected similarly, and the boost pressure will lag by a corresponding amount.

The pressure at the sliprings will no longer be that of the supply plus or minus boost, but the resultant of the two with a phase angle of more than zero and less than 180 degrees. Such resultant would therefore be less than their sum with positive boost, and greater than their difference with negative boost, thus requiring a wider range of excitation for a given range of pressure variation.

In some machines the booster field magnets are arranged so that they may be rotated a certain distance by hand wheel and screw gear, and the boost pressure thereby adjusted so as to be in step with the impressed pressure, its value then being directly added or subtracted.

## CHAPTER X

### *METHODS OF STARTING*

STARTING operations for rotary converters involve two main considerations, the actual starting from rest and bringing up to full speed, and paralleling with both c.c. and a.c. systems. To parallel on the c.c. side, the chief essential is that the machine pressure shall be equal to that of the system to which it is to be connected, while on the a.c. side not only is an approximation to this condition necessary, but the frequency of the machine and supply pressures must be equal, and the two must be in phase opposition, before the armature is directly connected to the supply.

The starting may be carried out from either side, as most convenient having regard to local conditions. Where the conversion is from a.c. to c.c. only, the starting is usually from the a.c. side, while when inverted running is required, c.c. starting may be provided. Where several converters are installed on one site and required to run either straight or inverted, the starting arrangements may be divided, some machines having a.c., and others c.c. starting; abnormal conditions being thus provided for.

#### C.C. STARTING

In c.c. starting the converter is used as a motor, a suitable starter being used to enable the machine to be

brought up to speed, after which the final adjustment of speed is made by field regulation until synchronism is obtained. Commonly, starters for this purpose are of the multiple switch type, where the steps of the resistance are cut out by closing a number of knife switches in succession, interlocking being fitted to ensure that the circuit-breaker controlling the starting may not be closed unless all resistance is in (switches open), and further, that the switches can only be closed in their proper order.

Where the synchronising switch is on the high-pressure side of the transformers the low-pressure switches must be open for c.c. starting; otherwise the armature would be practically short-circuited by the transformer secondary windings, and a very heavy current would be required for starting. These switches may be closed as the machine nears its full speed. With compound wound converters the series field winding must be cut out at starting, to prevent the weakening of the field which would be caused by the current being in the opposite direction, when motoring, to that when generating.

While it is not absolutely essential that the machine pressure should equal that of the supply when synchronising, yet the more nearly this is so the less disturbance will be created when switching in.

The speed of the machine as a c.c. motor depending on the field strength, it may occur that the flux which gives synchronous speed gives a value of the generated pressure different to that of the a.c. supply. When such difference exists more or less current will flow when the synchronising switch is closed, and this will lag or lead according to whether the machine or the supply pressure is the greater. The flux will be reduced or increased correspondingly by the armature reaction, and the speed

fluctuating, exchanges of power will take place between the two systems with more or less disturbance.

To prevent this, arrangements are usually made for the c.c. circuit-breaker to open just before the a.c. switch gets home, by means of a small trip switch operated by the latter. This is not required for converters fitted with a synchronous booster or an induction regulator, as in these the terminal pressure on the a.c. side may be adjusted without affecting the speed.

**Manual Synchronising.**—With reference to manual synchronising the following may be noted. When the machine is running at a speed slightly above that of synchronism its pressure will approach, pass through, and recede from opposition with the supply, going then through incidence and repeating this cycle of relationships at a low rate. Just before reaching opposition the machine will be lagging from the supply, while after passing opposition it will be leading.

If the switch is closed before opposition is reached, current will flow, and the incoming machine being lagging will be subjected to a motoring torque. Already running above normal speed it will tend to accelerate further and so pass through opposition at an increased rate, and now leading will act as a generator delivering power to the rest of the system, the consequent load torque then reducing the speed to its correct value.

When the switch is closed at the exact instant of phase opposition, no current flows (assuming the pressures equal) but the machine pressure will continue to advance in phase owing to the higher speed, so bringing load on until the speed is checked. It will be obvious, however, that the disturbance will be less in this case than in the former, where power is first taken from the rest of the system and then returned,

with the additional disadvantage of the higher speed at phase opposition.

When the switch is closed after phase opposition has been passed the shock is more violent the further the machine pressure has advanced, and the load picked up may cause the speed to drop below the proper value, with consequent oscillation of power between the machine and the system.

The same line of reasoning may be applied to switching in when the speed is below that of synchronism. When approaching phase opposition under these conditions the machine will be leading, and if the switch is closed too soon the current which flows produces a load torque, thus reducing the speed still further. The greater difference in the speed at exact opposition will necessitate a larger input of power, as the machine begins to lag, to bring it to synchronous speed, than if the switch were closed at the instant of opposition.

In each case, then, closing the switch before exact synchronism is reached causes an increase in the amount by which the speed of the incoming machine differs from that of synchronism.

It may be necessary, with some types of remotely controlled, or heavy manually operated synchronising switches, to commence the closing movement sooner in order that the actual connection may be made at the correct instant of synchronism. This, however, does not justify the statement sometimes met with, that the switch should be closed before synchronism is reached, which, as will be seen, will not bear examination.

### A.C. Starting

There are several methods in use for starting up from the a.c. side, either by means of an auxiliary, or "pony"

motor, or by having the converter itself designed for self-starting.

Auxiliary motor starting methods may be divided into two groups, manual synchronising, and self-synchronising, while self-starting converters are always self-synchronising.

With the self-synchronising methods now in use starting may be effected rapidly and simply, no skill being required on the part of the operator beyond the knowledge of the correct sequence of switching movements, these also being reduced to a minimum.

**The Induction Motor.**—As auxiliary motors are of the induction type, while the self-starting converter also operates as an induction motor when starting, a short description of this type of motor is given to enable the reader to understand the principles involved.

The stator of the induction motor is in the form of a laminated, hollow, cylindrical iron core, having coils wound in slots in its inner surface. These coils are so connected to a polyphase a.c. supply that the currents in them produce a rotating flux.

The rotor in its simplest form is a solid iron or steel drum which when placed inside the stator, so as to be traversed by the rotating flux, has e.m.fs. induced in it, these causing currents which circulate in the mass.

These currents react with the flux in such a way as to produce a motoring torque on the rotor, which is acting, in its various parts, as the current-carrying conductor.

A development of the foregoing, which may perhaps be more easily understood, is the squirrel-cage rotor, in which a number of bar conductors are embedded in slots in a laminated core, all their ends being joined together on each side, so that the winding somewhat resembles the

wheel used for tame squirrels or white mice to exercise in, hence its name.

When the flux rotates about such a winding e.m.fs. are induced in opposite directions in bars diametrically opposite (with a two-pole field), and currents circulate through these bars via the end connections.

The result is that the bars are urged to move by the interaction between the current and the flux, and the rotor is subjected to a torque in the direction of rotation of the flux.

On starting from rest the rate of cutting the bars by the flux is reduced and the induced e.m.f. thereupon falls off.

The speed will rise until the e.m.f. induced is of no greater value than is required to produce sufficient current for the torque necessary to overcome the mechanical resistances to rotation.

If the rotation were at synchronous speed the bars would be moving at the same rate as the flux and no effect would be produced in the rotor, a state of affairs impossible of attainment in practice.

The rotor therefore runs at some speed less than that of synchronism, the amount by which it falls short of the latter being known as the slip and varying with the load.

The greater the load on the motor the larger the rotor current required to maintain rotation, so that greater slip is necessary to produce the correct rate of cutting the flux for the e.m.f. required.

To improve the characteristics of the motor, the rotor winding may consist of coils, three for a two-pole stator winding, the coils being joined in parallel and the current flowing by the common junctions.

By bringing out one end of each coil to separate slip-rings the rotating field will produce three-phase pressures between the sliprings.

The relative movement between the rotating flux and the coils being the slip, the frequency of the slipring pressures will equal the slip revolutions per second, multiplied by the number of pairs of poles in the stator.

The brushes on the sliprings are connected to three resistances which have a sliding bridge contact member which connects all three. By moving this bridge along, the amount of resistance in the rotor circuits may be varied as required, the currents circulating via the coils, resistances, and the common junctions.

For a given speed of the rotor there will be a certain e.m.f. induced in its coils, so that by varying the resistance in the rotor circuits the speed may be regulated.

For example, if when running at a certain speed the resistance is increased, the current and consequently the torque is reduced, and the speed will fall until the greater rate of slip increases the e.m.f. induced to such a value as will produce the necessary current.

Induction motor stators may be wound so as to produce one or more pairs of poles in the field when, of course, the speed of the rotating flux falls in proportion to such number of pairs, exactly as in the synchronous machine.

The rotor will also have a corresponding number of coils, those two pole pitches apart being joined in parallel, thus forming three groups.

**Induction Motor starting, Manual Synchronising.**—As it is impossible for an induction motor to run at the synchronous speed of the flux, it would, if having the same number of poles as the converter it is intended to start, be unable to bring the latter to full speed.

To overcome this difficulty the auxiliary motor is made with one pair of poles less than the converter, and thus has a higher speed. When the slipring type is used the speed may be adjusted for synchronising by regulating

the rotor resistances. With squirrel-cage or solid rotors such speed regulation is not available and means are therefore provided for imposing an artificial load on the motor by loading the converter electrically.

This takes the form of a resistance connected between the a.c. terminals of the converter and capable of being varied by a rheostat. The converter set becomes virtually a motor-generator, and by varying the loading current by the rheostat the speed of the motor may be adjusted as required.

As a rule only a few steps are provided on the loading rheostat, and the common practice is to keep the regulator arm in a position found by trial to be the nearest correct, final adjustment to exact speed being brought about by varying the converter field and with it the pressure acting on the loading resistance.

In manual synchronising, auxiliary motor starting, the converter is simply run up to speed by the motor and synchronised by the operator, after which the starting switch is opened, cutting off the supply to the motor, the rotor of which then runs idly.

A switch is also provided to enable the loading resistance to be disconnected when synchronising is completed.

## CHAPTER XI

*METHODS OF STARTING*—continued

### Self-synchronising Methods

**Effect of connecting Alternators having Unequal Frequencies.**—Self-synchronising methods depend, in general, on the fact that two alternators when connected in parallel will endeavour to place themselves so that their respective pressures are in opposition, and will maintain this relation automatically.

This tendency exists even when their frequencies are unequal, the two machines being subjected to alternating torques, these torques being displaced so that when one machine is generating the other is motoring. To see the reason for this let us look at the conditions by means of vectors.

Two vectors representing alternating pressures are stationary with respect to each other only while their frequencies remain equal. Any change in the frequency of one of the pressures causes its vector to change its position in a forwards or backwards direction, according to whether the frequency increases or decreases.

The two pressures will then be completing their respective cycles in unequal times, with the consequence that one of them will gain upon the other at a rate dependent on the difference between the frequencies. For example, if of

two 50 cycle frequencies one is increased to 60 cycles, this will now gain one-fifth of a cycle on the other for each cycle completed by the latter, one going through 6 cycles and the other 5 cycles in the same time, viz. one-tenth of a second.

Of their vectors, one may be considered stationary while the other rotates about their common point at the rate of ten revolutions or cycles per second. If the 50 cycle vector is taken as the stationary one, the other will rotate forwards (anti-clockwise), while if the 60 cycle vector is stationary the rotation of the 50 cycle vector will be backwards. The two pressures will be in opposition at intervals of one-tenth of a second, passing through incidence midway between these instants, one having completed three cycles from opposition and the other only two and a half cycles.

When the difference between the frequencies is constant the speed of the rotating vector will remain constant, but if one frequency is continually changing with respect to the other, the rotational speed of the vector will also be continually changing.

It may help the reader to grasp these ideas better if we translate them into physical relationships by considering the relative positions of two armatures producing the pressures.

When their speeds and frequencies are equal corresponding points on each armature will occupy the same relative positions at every instant, and may therefore be said to be stationary with respect to each other. Increasing the speed of one causes it to advance relatively to the other by completing each revolution in a shorter time.

Frequencies of 50 and 60 cycles correspond (with a two-pole field) to speeds of 50 and 60 revolutions per second, so that while one armature has done 50 revolutions, the other will have done 60, thus gaining 10 revolutions in one second, or 1 revolution in one-tenth of a second.

If the two armatures were running side by side with their shafts in line and we imagine an observer on each, the position of each observer will remain unchanged, from the point of view of the other, while the speeds are equal. With the different speeds mentioned above the observer on the slower of the two will see his colleague pass him ten times per second going forwards, while the latter will see the first pass him an equal number of times, but backwards.

From this it will be seen that the representation of two pressures of different frequencies by two vectors, one stationary and the other revolving, gives a true picture of the facts.

In these circumstances the pressures are alternately leading and lagging from opposition with each other and consequently, as already stated, each machine is acting as motor and generator in turn, and being accelerated and retarded accordingly. It will be found convenient to consider the whole of these effects as occurring in the incoming machine only, the other being assumed as a supply system large enough to be unaffected thereby.

The effect of this alternating torque on the incoming machine is such that when the pressures are approaching opposition the difference in the frequencies tends to increase, while after passing opposition the difference is reduced. This is illustrated in Fig. 41, where the moving vector is distinguished by the arrow crossing its free end. In (*a*) the pressures are approaching opposition and $E_2$, already the faster of the two, is subjected to a motoring or accelerating torque, as shown by the broken-line arrow. In (*b*) $E_2$ has passed opposition and is being retarded by a load torque.

The effect of the incoming machine having a lower frequency than the supply may be seen by reversing the arrows indicating the direction of motion of the vector. The torque arrows will be unchanged, and the same result

as before is obtained, the difference between the frequencies is increased when approaching opposition, and decreased when receding therefrom.

This is seen to be in confirmation of the explanation given in the preceding chapter of the effect of closing the synchronising switch before the exact instant of synchronism is reached.

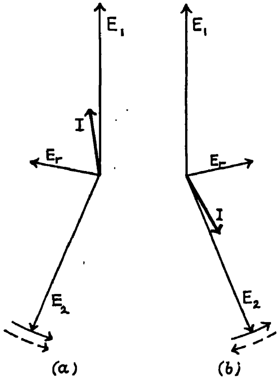



Fig. 41.

If the period of time during which the synchronising torque is operating is long enough, having regard to the value of the torque and the rotating mass to be acted upon, the change in the speed will be such that the machine will drop into step. If the difference in the speeds is too great, the time available is too short for the required change to be fully brought about, and the incoming machine will continue

to run at a speed which will fluctuate about a mean value, by virtue of the alternating torque.

**Resultant of Two Pressures of Different Frequencies.**—The resultant of two pressure waves of different frequencies has a wave form the maximum value of which is continually changing, being equal to the sum of the two fundamentals when these are in incidence, and to their difference when they are in opposition.

It is these variations which are shown by the synchronising lamps used when paralleling alternators, as described in Chapter VII. The rate of occurrence of the dark periods will be equal to the difference between the two frequencies, each bright period being made up of a number of cycles of a wave which has a varying amplitude and frequency.

The wave form resulting from two pressures of different frequencies is known as a heterodyne, of which the "beat" frequency, or rate of occurrence of the maximum amplitudes, is equal to the difference between the fundamental frequencies.

If the incoming machine was switched in when near synchronous speed and left to pull into step, such heavy currents would flow under the influence of the heterodyne as would cause serious disturbance to the rest of the system, as well as the possibility of damage to the windings of the machine itself. In self-synchronising methods of paralleling rotary converters, therefore, the object is to restrict the effect of the two pressures to some extent, so as to prevent undue disturbance, while at the same time allowing of sufficient current to pull the machine into step.

### TAP-STARTING

In the method now to be explained the converter is used as an induction motor for the time being when

starting, and its armature is therefore connected to the supply at the commencement, but the field circuit is broken by leaving the field switch open, so that no e.m.f. is induced in the armature as the speed rises. There is thus only the impressed pressure (which is reduced from that of the supply) present in the circuit until a selected moment, when the field switch is closed and the generated pressure appears, the synchronising action thereupon taking place.

The reduction of the supply pressure spoken of is obtained by means of special tappings to the transformer windings. These are arranged to give one or two intermediate steps before full pressure is applied, so keeping the value of the starting current within safe limits. Where there is only one intermediate step this may give about one-third, and with two steps one-quarter and two-thirds of full pressure. Tap-starting is the general name given to this method of starting synchronous machines.

When the polyphase supply is switched on to the converter armature, the currents set up a rotating flux therein, the direction of which will be opposite to that of the normal rotation of the armature. The damper winding fitted to the field poles of the rotary converter, if made continuous round the field system, is in effect similar to the squirrel-cage winding of the rotor of an induction motor. The rotating flux cuts the damper bars and induces e.m.fs. therein, which produce currents in exactly the same way.

The squirrel-cage being fixed in this instance, the torque developed between the armature flux and the squirrel-cage currents causes rotation of the armature itself, the motion being in the direction tending to reduce the relative speed between flux and conductors, or opposite to the rotating flux.

The converter will therefore run up to a certain speed

which gives a slip suitable for the torque required, as in the normal induction motor. The flux will still be rotating backwards round the armature at synchronous speed, but owing to the forward motion of the armature at a somewhat lower rate, the actual speed of the flux with respect to the damper winding will be equal to the difference between armature and synchronous speeds, this being the slip speed. Clearly the machine will be unable to attain any higher speed unless the conditions are modified in some way or other, but before going on to the question of how this is done, we may glance at the reason for certain precautions which have to be taken with tap-started converters.

**Alternating E.M.Fs. induced in Field Windings.**—As the rotating flux sweeps round the field system any residual flux in the main field poles is destroyed, and in its stead the magnets will be traversed by a flux which alternates in direction.

This alternating flux, linking with the field coils will induce e.m.fs. which, as the coils are connected in series, may result in a total pressure of a very high value, imposing severe stresses on the insulation of the coils. The field circuit is, therefore, preferably broken in several places by a multiple switch, so as to isolate each coil. The effect is most pronounced at first switching on the supply, owing to the high speed of the rotating flux. As the armature speed rises, the speed of the flux, and also its frequency in the stationary field poles, is reduced, and the e.m.f. induced in the field windings becomes less by reason of the lower rate of change of the flux.

Another effect which has to be guarded against is due to the self-induction of the armature coils. In those coils which are short-circuited by the commutator brushes, the opposing e.m.f. of self-induction produced by the alternating current has the effect of shunting the

current through the brush. As a result of this, when the armature is in motion, the sudden change of the current round any coil to full value as it leaves a brush causes a big increase in the self-induced e.m.f. and sparking occurs from the commutator bars to the brushes. This is particularly noticeable when first switching on the supply and when changing from one set of tappings to another while running up, on account of the relatively large currents which flow at these times. To avoid this sparking, tap-started converters frequently have gear fitted for raising the commutator brushes during the starting operation.

**Alternating Pressure on Commutator.**—When the converter is running as an induction motor at a speed less than synchronism there will be alternating pressures between points 180 degrees apart on the commutator, these pressures being caused by the movement of the rotating flux across the armature conductors.

At all speeds of the armature the relative motion between the flux and the conductors is the same, the flux always rotating backwards round the armature at synchronous speed. There is consequently an e.m.f. induced in the conductors which has the same frequency as the supply, and this will be so at all speeds of the armature, the rotation of which merely varies the speed of the flux with respect to the ground.

Between points on the commutator 180 degrees apart, then, there will be alternating pressures having the same frequency as the supply, and when the armature is stationary these pressures will appear between adjacent sets of commutator brushes with the same frequency.

When the armature is rotating, however, the speed of the flux and consequently of the induced pressures in the conductors, while still at synchronous rate round the armature is reduced with respect to the stationary com-

mutator brushes. The pressure between the latter will therefore have a lower frequency, this being, in fact, equal to the difference between the supply frequency and that corresponding to the rotational speed of the armature.

For example, with an eight-pole machine and a supply frequency of 50 cycles, the speed of the flux will be 750 revs. per minute, or 12·5 per second. If the armature is rotating forwards at one rev. per second the actual speed of the flux with respect to the brushes will be 11·5 revs. per second, and the field having four pairs of poles the frequency at these brushes will be four cycles per rev., or 46 per second.

This is the frequency of the slip, or the product of the slip speed in revs. per second and the number of pairs of poles.

When the armature is stationary the slip is equal to the supply frequency, while with the armature at synchronous speed the slip is zero and the pressure at the commutator brushes will be constant in value, that is, a continuous pressure.

It is to be observed that these pressures are due to the self-induction of the armature winding, being produced by the flux set up by the currents therein, and as such they will be 180 degrees out of phase with the supply pressure, or in opposition.

It follows, then, that when the pressure impressed to a pair of 180 degree tappings reaches maximum, the pressure between those commutator bars at the other ends of the coils to which the tappings are made will be maximum also. If the occurrence of impressed maximum coincides with the arrival of the tapping coils at the brush position, this maximum will appear at the brushes, which will be of the same sign at that instant as their associated tappings. For example, at such an instant the tapping which is of

positive sign, the pressure being into the armature, will have the self-induced armature pressure in opposition, that is, out of the armature, and the corresponding commutator brush will therefore be positive also.

If the armature is running below synchronous speed, the tappings will have travelled less than 360 degrees when next maximum occurs in the same direction, so that by the time they get to the brush position the pressure will be less than before. After one quarter of a slip cycle the tappings will be equidistant from the brushes at impressed maximum, and the pressure at the brushes will be zero. A further quarter of a slip cycle will bring the tappings again to the brush positions when maximum in the direction first considered occurs. Now, however, the tappings have slipped 180 degrees, or one pole pitch, so that although the same tapping is positive again at this instant, its coil is now under the other brush, that is, the signs of the commutator brushes are reversed.

**Self-synchronising.**—Two brushes of different sign having been left down on the commutator for the purpose, a voltmeter connected to the terminals of the machine will show by the oscillations of its pointer the frequency of the pressure at the commutator, and therefore the amount of the slip. This voltmeter is of a type, such as the moving coil instrument, which shows the direction of the pressure as well as its value, and with a scale reading either way from a central zero.

At first, the slip frequency being high, the moving parts are unable to follow the rapid fluctuations of the pressure, but as the slip becomes less the pointer begins to oscillate about the zero mark. At the highest speed of the machine the swings will occur at a low rate and equally in each direction, the maximum reading either way indicating that 180 degree tappings have arrived at the

brush positions at the same time as the occurrence of maximum impressed pressure.

At each of these instants the armature is in a position correct for synchronism, so that if the field connections are correct, the closing of the field switch will produce a flux which will induce in the armature pressures in the same direction as those self-induced, that is, in opposition to the impressed pressures.

The frequency of this generated pressure depends on the speed of the armature, and will, of course, be lower than that of the supply. It will, therefore, drop behind from phase opposition and the resultant thereupon arising will produce a motoring current which, if the difference of speed is not too great, will accelerate the armature into synchronism.

At each of the two instants indicated by opposite swings of the voltmeter the same arrangements of field connections will give the required polarity to the field magnets.

This arises from the following considerations.

The direction of induced pressure required in any conductor is the same in each case, as the direction of impressed pressure is the same in each case.

The conductors, however, will occupy different positions at each of the two instants, these positions being separated by one pole pitch, therefore, if the field were constantly excited, they would be under poles of opposite sign at the different times we are considering.

The field circuit is energised from the commutator brushes, however, and we have seen that these change their signs for each half-cycle of slip. The field current will therefore be reversed to correspond, and consequently at each successive instant of synchronism any conductor will be under a pole of the same sign.

If the machine is run up with the field switch closed the reversals of field polarity at each half slip cycle will be brought about automatically by the reversals of pressure at the commutator.

Phase opposition between generated and impressed pressures will then occur twice per slip cycle and the armature will be subjected to an alternating torque, retarding as opposition is approached and accelerating as this is receded from. This torque will be superimposed on the induction motor torque until finally the change of speed produced during the acceleration period will be sufficient to bring it up to synchronous rate and the machine will be pulled into step with the supply. This it will do, from the nature of things, with perfect indifference to the direction of pressure at the commutator, this depending on the particular half of the slip cycle during which synchronism has been reached.

It is, however, necessary that a certain definite direction of pressure is obtained in order to allow of the machine being paralleled with other plant on the c.c. side. In practice, therefore, the field switch is kept open until the machine is at its maximum speed, *i.e.* the voltmeter oscillations at their lowest rate.

As the pointer reaches its maximum reading in the desired direction, indicating correct c.c. polarity, the field switch is closed and the generated pressure builds up, the machine then pulling into step.

Clearly, the higher the speed reached as an induction motor, the less effort will be required to bring the speed to synchronous value, and the smaller will be the current for the power input necessary to do this.

For this reason, as well as to reduce the starting current required, some makers fit tap-started converters with ball or roller bearings, which with their small frictional

losses, have the double advantage of enabling the machine to run with smaller slip and of reducing the power required to bring about the change of speed when synchronising.

**Synchronising with Wrong C.C. Polarity.**—It may occur that owing to delay in closing the field switch, the field has not time to build up sufficiently to pull the machine into step at once, and either one of two things may happen. The generated pressure is constant in direction at the brushes whereas the self-induced pressure will reverse as the slip continues. If the former is greater than the latter actual reversal of the resultant pressure at the commutator will be prevented, while if the converse holds the pressure will reverse and the machine will pull into step with incorrect polarity.

With the first of these the generated and impressed pressures will go through phase incidence, and a heavy current will flow, with oscillations of power from and to the rest of the system as the machine passes through incidence to opposition once more and finally pulls into step. Obviously this is a state of affairs to be avoided, if possible, by correct closing of the field switch.

If incorrect polarity is obtained this may sometimes be remedied by opening the field switch once more, when synchronism may be lost and induction motor running be resumed, another attempt then being made.

Often, however, with the reduction of the generated pressure consequent on breaking the field circuit, the current will lag sufficiently to maintain a flux strong enough to keep the machine in synchronism.

It will then run on as a synchronous motor, the residual flux being augmented by the magnetising component of the armature current.

To provide for this, the field switch is usually arranged for double-throw operation, so as to reverse the connections

to the field circuit. When synchronism with incorrect polarity occurs this switch is thrown over, so reversing the field current, the flux thereupon falls to zero and the armature begins slipping once more. The conditions are now as when first running up, with the important difference that the field connections are reversed. Thus when the tappings coincide with the brush positions at impressed maximum the direction of the field current will be such as to create a flux which will induce a pressure in the same direction as that impressed. This generated pressure, however, is opposite to that of self-induction, so that any attempt of the field to build up is neutralised by the opposing pressure induced thereby. The same thing occurs at each half-cycle of slip, so that while the field connections are reversed the machine cannot pull into step.

After the field is reversed, then, and synchronism is lost, the switch must be brought to the open position again and the next swing of the voltmeter in the required direction awaited. The operation of correcting the polarity in this manner is known as " slipping a pole," from the fact that when it is done, a given point on the armature drops back one pole pitch relatively to a similar point on a synchronously running armature. Actually, however, any odd number of poles may be slipped, this depending on the number of slip cycles which elapse between losing and regaining synchronism. Slipping an even number of poles would result in incorrect polarity again.

It should be observed that the real function of the reversing switch is not to reverse the c.c. polarity, but only to kill the field flux to ensure synchronism being lost.

**Changing to Full Pressure Tappings.**—When the converter has pulled into step, as indicated by the c.c. voltmeter remaining steady in the proper direction, the

supply may be changed over from the low-pressure tappings to full pressure. In making the change it is necessary that the low-pressure connections should be broken before the full pressure connections are made, to avoid the sections of the transformer windings between the tappings being short-circuited by the switches.

This means that for a brief space of time the converter is disconnected from the supply, and if the operation were unduly prolonged synchronism would be lost by the machine slowing down. To prevent this the change over should be carried out as speedily as possible, and where independent switches are used it devolves on the operator to make the movements in the proper order and without delay.

Modern arrangements take the form of switches so connected mechanically that one movement of an operating lever opens and closes the connections in their correct sequence, while any hesitation or delay is met by the lever becoming locked in the intermediate or "off" position, whence it can only be moved to the low-pressure or "starting" position, thus preventing the "running" position being gained after the machine has had time to lose synchronism.

After lowering the remainder of the commutator brushes the converter is ready for paralleling on the c.c. side.

# CHAPTER XII

## *METHODS OF STARTING*—continued

### Auxiliary Motor with Series Reactances, Self-synchronising

In this method a separate starting motor is used to bring the converter up to speed, after which the slip-rings are connected to the supply with reactance coils in series to limit the current in the circuit while the machine is synchronising.

A simple diagram of the connections is given in Fig. 42, where, to avoid confusion, only those to two 180 degree tappings are shown, the machine being assumed as of six phases.

The method of transformer connections known as diametrical is used (see Chapter XIV.), in which the six phases at the converter are derived from three entirely independent windings at the transformer. The machine is thus supplied by three single-phase circuits, one of which is shown in the diagram, and the other two, identical in arrangement, indicated by the numbering of the various connections to switches, etc. As will be seen from Fig. 42, a switch is provided in one lead of each pair, these being combined into a three-pole switch. When this is open each of the circuits is broken and no current can flow.

When the supply is switched on to the primary windings of the transformer the secondary pressure will appear on

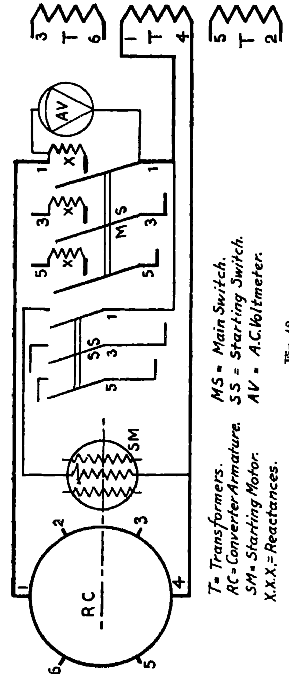

T = Transformers.
RC = Converter Armature.
SM = Starting Motor.
X.X.X. = Reactances.
MS = Main Switch.
SS = Starting Switch.
AV = A.C. Voltmeter.

Fig. 42.

the a.c. voltmeter SV which is connected across the break in the secondary circuit at the main switch. On closing the starting switch the motor begins to run the converter up, and the field circuit of the latter being closed it begins to generate its own pressure, which will be indicated on the c.c. voltmeter, connected in the usual manner.

There will now be two pressures of different frequencies in the circuit formed by the transformer secondary and the converter armature, and their resultant will be shown by SV pulsating at a rate equal to the difference in the frequencies. The actual current in this circuit will be negligible, being only the very small one taken by the voltmeter, the effect on the commutator pressure will therefore be nil and the c.c. voltmeter will rise steadily as the generated pressure builds up.

As the converter frequency increases with the rising speed the beats of the resultant pressure will get slower, the instants of opposition and incidence of the fundamentals occurring at the minimum and maximum readings respectively, on the a.c. voltmeter. The starting motor, which has one pair of poles less than the converter, is designed with such slip that its maximum speed is somewhere about synchronous speed for the converter, while the position of the field regulator for starting, as found by the makers on test, allows the generated pressure to build up to a certain value at the same time, usually about 100–150 volts on the c.c. voltmeter.

When the specified figure is reached, and at a time when the a.c. voltmeter, which is now pulsating slowly, is near the lowest point of its swing, *i.e.* pressures approaching opposition, the main switch is put into the intermediate position, connecting the converter and the supply with the reactances in series. The two pressures still having slightly different frequencies, will begin to depart from opposition

once more and a current will flow producing a synchronising torque, thereby pulling the converter into step. The current is kept within safe limits by the reactances, even if synchronism should not be attained at once and the pressures should pass through incidence.

When the machine is in step the a.c. voltmeter falls nearly to zero and remains steady. The main switch, which has been prevented by a catch from being pushed right home at one movement, is now drawn back slightly, when the catch falls and the switch may be closed into the running position, short-circuiting the reactances and connecting the machine directly to the supply. The main switch is sometimes arranged so that the final movement operates a device which trips the starting switch; where this is not so done the starting switch is opened by hand, and the converter is ready to be connected to the c.c. bus-bars.

**Failure to Synchronise.**—It may rarely happen that the machine will fail to pull into step, as the result of some item of the starting conditions not being in order. As the causes of this are often not easily apparent to the operator, it is convenient for him to be able to recognise the condition should it arise, so that he may take action for its remedy without undue loss of time.

Failure to synchronise is indicated by the a.c. and c.c. voltmeters continuing to pulsate without slowing down, after the main switch is put on to the choker contacts. If the latter movement has been performed too soon, the speed will be too low to allow of the synchronising torque bringing the machine into step, and slipping continues. The starting motor is then, in effect, acted on by two pressures of different frequencies in parallel; its torque therefore falls off, and it may be unable to accelerate any further, but will continue to run at a speed which is too low for

synchronising. In these circumstances the converter field should be weakened, thus reducing the generated pressure, when the speed will be heard to rise, and the pulsations of the voltmeters will slow down until the machine pulls into step.

Wrong position of the field regulator giving too strong a field, or a.c. supply pressure below normal, tend to cause failure to synchronise with the converter below correct speed.

On the other hand, if the field is too weak, or the supply pressure is above normal, the machine may go above synchronous speed and stay there, refusing to pull down into step. The opposite procedure to the foregoing should be followed in this event; strengthen the field and the speed will fall.

**Reversal of Polarity.**—When the converter has been connected to the a.c. supply with the reactances in series, a similar state of affairs exists on the commutator to that described for the tap-started machine. The current in the armature produces an alternating pressure at the commutator brushes with slip frequency, and this is modified by the continuous pressure generated by the rotation of the armature conductors through the field. If the continuous pressure is the greater of the two, their resultant merely fluctuates, as shown on the c.c. voltmeter; but if the alternating pressure should be the greater, the resultant at the commutator brushes will reverse and the machine may pull into step with incorrect polarity.

A reversal of polarity may sometimes be prevented when about to occur, by prompt handling of the field regulator.

If, on putting the main switch on to the choker contacts, the c.c. voltmeter is seen to make a rapid swing towards the zero of the scale a reversal is imminent, and the field

should be strengthened as quickly as possible to build up the generated pressure. Should the reversal take place in spite of this, the field should be weakened again to try and prevent the machine pulling into step and to encourage another reversal, afterwards being strengthened once more to retain the correct polarity so obtained. This, which perhaps reads as rather complicated, is in reality very simple, when once the underlying principle is grasped, and is a procedure which is actually put into practice in a case within the author's own knowledge.

If the machine synchronises with wrong polarity it should be switched out and allowed to come to a stand, or nearly so, and then restarted with a weak field, so as to induce another reversal. By keeping the generated pressure down and closing the main switch on to the choker contacts just before synchronous speed is reached, it should be possible to get reversals at the commutator brushes, when the correct polarity may be selected by strengthening the field as the c.c. voltmeter is making a swing in the required direction.

When a reversal cannot be corrected in any other way, a common practice is to stop the machine, lift and insulate the brushes from the commutator, and energise the field from the bus-bars by closing the c.c. circuit-breakers and switches, after which a fresh start is made. This method is not to be recommended if it can be avoided, as in the absence of a discharge resistance between the terminals of the field circuit, a severe strain is imposed on the insulation of the field coils by the e.m.f. of self-induction when the circuit is broken again, many cases having occurred of field coils breaking down on this account.

Normally, such things as failure to synchronise or reversal of polarity should be rare, as the operator has in his a.c. voltmeter a reliable indication of the difference

between the generated and supply frequencies, and can therefore select the most favourable moment for closing the main switch, when, with the c.c. voltmeter well up, the result should be certain.

When, however, things do not go off "according to plan," such hints as the foregoing may be of assistance to him in finding a way out of the difficulty.

### Series Induction Motor starting, Self-synchronising

In this method separate reactances are not used, the windings of the starting motor being connected in series with the converter armature instead; the arrangement is shown in Fig. 43.

When the starting switch is closed the set runs up, the starting current flowing through the windings of the converter as well as those of the motor. The armature fluxes produced by the current will be too weak to destroy the residual flux in the field magnets, and although the field circuit is closed, the high inductance of the coils prevents the alternating pressure on the commutator from producing sufficient current to affect the residual flux.

The generated pressure, therefore, builds up in the proper direction and the actual pressure at the commutator brushes will be the resultant of the generated pressure, which is constant in direction, and the reactive pressure due to the starting current, which is alternating.

The generated pressure soon reaches a value which prevents the reversal of the resultant, and thereafter the latter simply pulsates while remaining constant in direction. The variations of the pressure at the commutator brushes are shown on the c.c. voltmeter, while the resultant of the supply and generated pressures on the a.c. side is indicated

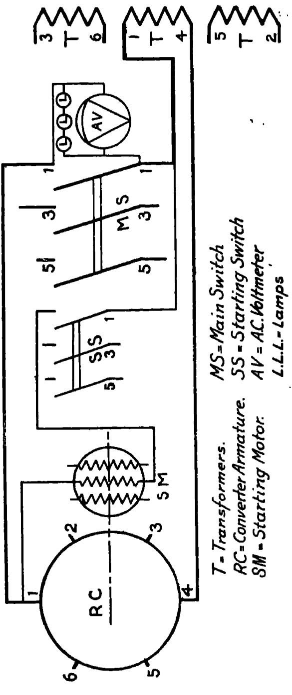

T = Transformers.
RC = Converter Armature.
SM = Starting Motor.
MS = Main Switch
SS = Starting Switch
AV = A.C. Voltmeter
L.L.L. = Lamps
RC
SM
SS
MS
AV

Fig. 43.

by the a.c. voltmeter connected across the main switch (see Fig. 43).

When near synchronous speed the armature will be acted on by a synchronising torque in the usual way and may pull into step without further delay.

It may occur, however, that the motor, which has one pair of poles fewer than the converter, runs the set above correct speed, the effect of the two pressures at different frequencies then pulling the speed down again until the machine synchronises, which is shown by the a.c. voltmeter falling nearly to zero and becoming steady. When the machine is in step the voltmeter will not go quite to zero owing to the pressure drop across the starting motor windings which are in parallel with the main switch, while any difference between the values of converter and supply pressures will give an increased reading on this voltmeter. The field regulator should then be adjusted until the minimum reading is obtained, when the main switch may be closed and the starting switch opened, the machine then being ready for connecting to the c.c. bus-bars. The starting position of the field regulator is specified by the makers, and the machine should run up and synchronise without this being disturbed.

Indicating lamps are often provided in parallel with the a.c. voltmeter, and where this is done they must be suitable for twice the normal supply pressure. The voltmeter is then usually of a pattern reading up to 200 volts only, and provided with a plug to break the circuit, this plug being kept out when starting. With this arrangement, when the machine is being run up, the lamps will light up and darken at a rate depending on the slip frequency. When the lamps have ceased to go to their full brilliancy and are out, or nearly so, the machine will be in step. The c.c. voltmeter will probably be at the

upper end of its scale, and the field should be reduced until about the normal c.c. pressure is shown and the a.c. lamps are out. The plug is then put in to bring the a.c. voltmeter into use for the final adjustment between the pressures before closing the main switch.

The a.c. voltmeter plug should be removed as soon as the main switch is closed, a dummy receptacle being provided to hold it when not in use. If the plug were left in when starting, the voltmeter would have almost the full supply pressure across its terminals at switching in, and the voltmeter fuses would blow.

**Failure to Synchronise.**—If the generated pressure rises too quickly or the a.c. supply pressure is below normal, the starting motor may be unable to bring the converter to a speed from which it will synchronise: the remedy is the same as in the series reactance arrangement, weaken the field to allow the motor to speed up. Failing to synchronise when above synchronous speed is not likely to occur unless the generated pressure is abnormally low or the supply pressure abnormally high; in such a case, however, strengthening the field will bring the speed down.

It may occasionally happen when things have been going normally, the machine having risen above synchronous speed and pulling down again, that correct speed is passed and failure below speed occurs. This is probably due to the fact that the arrival at correct speed has coincided with incidence of the pressures, while at the instants of opposition preceding and following this the difference in speed has been too great for the synchronising torque to effect the required change. The converter being now below correct speed, weaken the field to allow the motor to speed up.

It should be observed that when the machine has failed to pull into step, as shown by the c.c voltmeter dropping

back with rapid pulsations, the starting motor is being subjected to a pressure having a maximum value equal to the sum of the generated and supply pressures, being in series with these instead of, as with separate reactances, in parallel. This condition should be remedied without loss of time, to avoid the overheating which would otherwise occur in the motor.

The author has known of a case where a converter with the series motor starting arrangement absolutely refused to pull into step, possibly owing to the 3-phase supply being badly out of balance. Such an occurrence must be extremely rare, but if met with and the machine is urgently required in service, it is not really necessary to give up and wait until conditions improve, provided that other c.c. energy is available.

After running up as far as possible with the starting motor, the starting switch should be opened, the continuous pressure brought up, and the machine paralleled and switched on to the c.c. bus-bars while running on with its own momentum. Time may be saved by preparing the c.c. switchgear so as to leave as little to be done at the last moment as possible. The machine may then be brought up to speed as a c.c. motor by weakening the field, when the relation between the slipring and supply pressures will be indicated by the synchronising lamps and voltmeter, and all will be in order for manual synchronising. It would be advisable, when this is being done, to have a second person at hand to trip the c.c. circuit breakers as the main a.c. switch is being closed, to prevent interchange of power between the two systems.

It is perhaps hardly necessary to say that such procedure as the foregoing should only be carried out by persons who are thoroughly conversant with the principles involved, and after due consideration of all the circumstances.

**Reversal of Polarity.**—This may be caused by wrong position of field regulator giving too weak a field, or by high supply pressure. The c.c. voltmeter first rises in the proper direction, and then after the pulsations have slowed down, showing approach to synchronous speed, the pointer goes to the wrong side of the zero, a reverse reading scale of 100 volts being usually provided to enable this movement to be clearly seen.

Modern practice is to arrange alternative supply to the field circuit from the bus-bars by a change-over switch. If reversal occurs the switch is put over immediately to the bus-bar supply to energise the field correctly, and then brought back to the running position when the voltmeter reads in the proper direction.

Where this arrangement is not fitted, or other c.c. energy is not available, the following procedure is sometimes effective.

When reversal occurs allow the machine to pull into step, *i.e.* synchronising lamps out, and then without closing the main switch, weaken the field as much as possible. If this can be carried far enough the starting motor will pull the converter out of synchronism by raising the speed, and the commutator pressure will reverse as the armature slips a pole in the forward direction. When the c.c. voltmeter reads in the proper direction the field should be strengthened at once and the machine will pull into step with correct polarity.

If the field regulator has not sufficient range for this method to be used, the machine should be shut down after reversal has taken place, and re-started with the regulator in a position to give a weak field. By keeping down the generated pressure as the machine speeds up, the pressure at the commutator brushes (the resultant of that generated and the reactive pressure due to the armature current)

will alternate in direction, and when near synchronous speed the alternations will be comparatively slow and will be shown on the c.c. voltmeter. When at their slowest rate and as the pointer is commencing a swing in the required direction, the field should be rapidly strengthened, when if the moment has been correctly chosen the pressure will build up and the machine pull into step.

The rotating flux in the armature at starting is usually too small to destroy the residual flux in the field magnets, and reversal of polarity almost invariably arises from the generated pressure not fully counteracting the reactive alternating pressure on the commutator. Strengthening the field to assist the generated pressure if it shows signs of failing to reach a safe value before synchronous speed is attained, will prevent reversal from this cause.

**Modified Arrangements of Series Motor Starting.**—For large machines the starting arrangements are sometimes slightly different to those just described, the starting switch being of the double-throw type. In the first position of this the motor circuit is independent of the converter armature, thus avoiding the possibility of the starting current demagnetising the field poles. When the set has run up to speed the switch is changed over to the second position, putting the motor windings in series with the armature to enable the machine to synchronise.

In some cases the field switch is kept open until the c.c. voltmeter indicates by its pulsations that the converter is at synchronous speed, and then closed as the pointer rises in the proper direction, so that the field builds up correctly and the machine pulls into step with the right polarity.

With another arrangement the set is run up with the starting motor in series and the field switch open. When at synchronous speed the main switch is closed on to

intermediate contacts, connecting the supply to the armature with resistances (known for some reason as "kicking coils") in series, the field switch then being closed as the c.c. voltmeter comes up in the right direction.

**Series Motor with Same Number of Poles as Converter.**—In the latest development of the series motor self-synchronising method of starting, the auxiliary motor has the same number of poles as the converter, and has an unwound rotor consisting of a solid cylinder of iron or steel. The stator windings have tappings so that the whole, or a part only, of the winding may be energised by means of a double-throw switch.

With this switch in the starting position, the whole winding is active, and the motor has a high starting torque without an unduly large current in the supply circuit. At its full speed under these conditions, however, the slip is too great and the current too small to allow of pulling into step. The switch is then put into the second position, so cutting out a part of the motor winding, causing an increase of the current, and with it, of the flux density. A greater e.m.f. is now induced in the rotor, and the increased current which results brings about a reduction of the slip, that is, the speed is raised nearer to that of synchronism. At the same time the synchronous torque is increased by the larger current flowing through the armature of the converter, which is thus enabled to pull into step and remain so. The operation is completed by closing the main switch when the continuous pressure has built up fully, and then opening the starting switch.

A change-over switch is provided in the field circuit, so that should the polarity become reversed, the field connections may be reversed to kill the flux and cause the machine to lose synchronism. The field switch is then brought to the open position, and the set now running at

the speed of the starting motor, or below synchronism, the alternating pressure of slip frequency at the commutator brushes is shown by the c.c. voltmeter. Correct polarity is then obtained by closing the switch into the running position as the voltmeter rises in the desired direction, and the machine synchronises once more.

# CHAPTER XIII

## *PARALLEL AND INVERTED RUNNING. 3-WIRE BALANCING*

**Converters in Parallel.**—As with c.c. generators, the behaviour of rotary converters in parallel depends on the characteristics of the separate machines, each with its transformer and any auxiliary apparatus for pressure variation being considered as a unit. These are matters which are outside the control of the operator, and in general it may be said that converter sets which are to run in parallel with each other are designed with similar characteristics. The operator, however, is more nearly concerned with the question of the division of load between the machines and the adjusting of the power factors so as to get the best operating conditions with different loads.

In view of the many different arrangements which are used for the purpose of obtaining variation of the pressure generated by rotary converters, it would be an almost endless task to attempt to enumerate the actions which may take place with various combinations of these. The reader will find that a thorough grasp of the principles involved in methods of pressure variation will best help him to understand what takes place with a given installation, as well as to form an idea of what to expect with an arrangement of which he has had no previous experience. Reference will therefore be made here only to the more

general aspects of parallel running, leaving the reader to apply the knowledge gained elsewhere in this book to particular requirements of any case he may have to deal with.

On account of the various pressure drops in the equipment, as in transformers, cables, and slipring and commutator brushes, the rotary converter has a drooping characteristic, this being, however, usually somewhat flatter than that of the ordinary shunt-wound c.c. generator. In general, therefore, converters will run stably in parallel.

Machines may be made to carry equal or unequal portions of the total load by variation of the pressure generated, and this will have its effect on the power factors according to the method of pressure control in use.

Plain shunt-wound machines will have their power factors affected to the largest extent, and those with reactance control to a lesser degree.

Machines with induction regulator or synchronous booster may have the power factor kept constant over a very wide range of load, depending, of course, on the amount of pressure variation designed for.

Compounded converters must have their series windings paralleled by an equalising connection to ensure stability, this including the series winding on the field of a synchronous booster where such is fitted.

Converters required to run in parallel with ordinary c.c. generators may be found to take more than their share of varying loads on account of their flatter characteristics, necessitating constant attention to the field regulator to maintain equal division of the load.

In such instances the converter field is sometimes fitted with a reverse or differential series winding, which by weakening the field as the load increases gives the required drooping characteristic.

**Converters in Parallel on Both Sides.**—Converters will not run stably when they are directly connected to the same a.c. supply in addition to being in parallel on the c.c. side.

By this is meant machines connected to the same transformer secondary or other a.c. system, so that there is a complete copper path between them on both a.c. and c.c. sides.

There is then a system of parallel paths formed by the armatures, bus-bars and connections thereto, and if a difference exists between the pressures generated in the two armatures currents will circulate in this system.

Each of the paths for this current being made up of certain lengths of cable, bus-bars and surface contacts between brushes and commutators or sliprings, their resistances will inevitably differ, and consequently the current will have a different value in each path.

The result of this will be that brushes of opposite sign on the same machine will be carrying different values of current, and if an external load is being supplied the positive brushes on one machine and the negative on the other may be loaded above their rated capacity, while the other brush sets are doing little or nothing.

Such a state of affairs is altogether inadmissible, if for no other reason than the sparking which would occur on the commutator.

The operation of two converters from one transformer secondary or one alternator winding without transformers is not practicable therefore, unless means are provided to prevent the irregularities just mentioned, and for this purpose a balancing transformer is used.

This has two sets of windings on the same core, these being connected in the a.c. supply leads, one in series with each converter, and so arranged that the load currents

flow in opposite directions round the core. The m.m.fs. produced therefore oppose each other, and when the currents are equal no flux is produced in the core.

Any inequality in the currents disturbs the balance and the flux which then arises produces a choking e.m.f. in the winding having the larger current, and a boosting e.m.f. in that with the smaller current, so restoring the current balance.

When one converter only is on load, only one winding of the balancing transformer will be energised and this will add reactance to the circuit. To avoid this a switch is provided to put both windings in parallel at such times and so produce opposing m.m.fs. in the core.

For 6-phase machines the balancing transformer need only be connected in three of the phases spaced 120 degrees apart, and will then have a core of three limbs, each carrying the two windings of one phase. The arrangement of the connections is shown in Fig. 44, those for two out of six phases only being given to avoid confusion.

The chief application of the balancing transformer is where rotary converters are used in conjunction with a low-pressure alternator for supplying a c.c. load. This method of producing c.c. energy has the advantage of enabling the efficiencies of high-speed turbines to be obtained without the drawbacks of commutation troubles with high-speed c.c. generators, or the alternative of reduction gearing to enable low-speed generators to be turbine driven. Such low-pressure alternators are usually connected to give six phases, and two converters are used, each of half the rated capacity of the alternator.

**Protection against Excessive Speed.**—To guard against excessive speed being reached by the converter, as might happen in certain circumstances, an over-speed protective device is usually fitted on the shaft. This acts by centri-

fugal force and closes a pair of contacts which complete the circuit of a tripping coil on the c.c. circuit-breakers.

When running in parallel with other c.c. generators, failure of the a.c. supply to the converter will cause it to

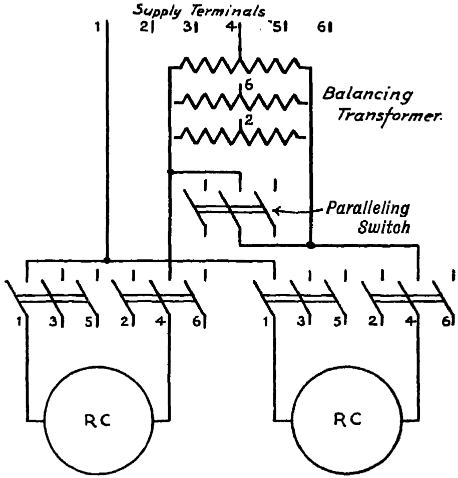



Fig. 44.

run as a c.c. motor, and its speed will then depend on the field excitation. If this should be below normal the speed will rise and may reach a dangerous degree in spite of the reverse current tripping gear on the c.c. side. To avoid the possibility of damage to the armature from this cause

the over-speed device is adjusted to operate at a safe value above normal speed.

**Testing Over-speed Device.**—It is desirable that the working of the device should be tested from time to time to ensure its reliability, and the manner in which this may be done depends on the starting arrangements of the set.

With c.c. starting the machine may be run up in the usual manner, and the speed raised by weakening the field until the circuit-breakers trip. This is assuming that the over-speed trip coils are fitted to circuit-breakers which are in use during the starting operation. If, as is often the case, there is a separate circuit-breaker for starting, it may be possible to close the running circuit-breakers with safety, this depending on whether switches are fitted in both c.c. leads in addition.

If this cannot be done the following method may be used, which is also applicable to any case, provided that there is other c.c. generating plant in parallel.

The converter is taken when connected to both a.c. and c.c. systems, and the a.c. oil switch tripped, so that the machine runs as a c.c. motor ; the speed can then be raised, until the circuit-breakers trip, care being taken to see that it is the over-speed and not the reverse current device which operates, to avoid being misled.

A test of this kind is not complete unless the actual tripping speed can be observed by a revolution indicator. Without this an unsafe speed may be reached and the test be worse than useless. In any case, if the device does not operate at the speed at which it is intended to, adjustment should be made until it does.

Where starting is by an induction motor having one pair of poles less than the converter, this may be used to test the over-speed device, provided that the c.c. circuit-breakers can safely be closed while the machine is standing.

The starting motor will run the converter above synchronous speed, but the actual excess speed has definite limits imposed by the frequency of the supply. If the over-speed device trips under these conditions it may be assumed that the tripping speed is a safe one, although its actual value is not known.

When the circuit-breakers open, an auxiliary contact opens the tripping circuit, so preventing burning of the contacts which would occur if this circuit was broken by the centrifugal device as the machine slows down.

## Inverted Running

There is nothing inherent in the rotary converter which renders it more suitable for converting from a.c. to c.c. than in the opposite direction. General usage has recognised the term "inverted" as applying to the conversion from c.c. to a.c., but has not adopted a corresponding term for conversion from a.c. to c.c., although the latter is sometimes called "straight" running, and for the sake of brevity will be so referred to here. For the simple duty of conversion any machine will perform equally well in either direction, but when running inverted problems arise in connection with the speed and power factor which do not exist with straight running.

**Speed Control.**—When the power input is from the a.c. side the speed of the machine clearly depends on the frequency of the supply, but when inverted, and with no other synchronous generators in parallel, the speed, and consequently the frequency, depends on the field excitation. This will be affected by the phase relationship between the current and pressure, so that any change in the value of the wattless component of the current, whether due to

changing power factor or varying load, will vary the field flux and so alter the speed. A speed and frequency liable to change with each variation in the load or power factor is wholly undesirable, while the possibility of dangerous speeds being reached has also to be considered.

A common method of correcting this is to provide a shunt-wound exciter coupled to the converter shaft. For inverted running the converter field circuit is supplied from the exciter which is designed to operate with a relatively low flux density in its field magnets, so that any change in its own exciting current results in a large variation in the flux. Any increase in speed produces a rise in the exciter terminal pressure which is amplified by the strengthening of the exciter flux so caused; this in turn, by increasing the excitation of the converter, opposes the change of speed, which is kept within small limits. A series winding on the converter field magnets is also an advantage, the changing armature reaction with fluctuating loads being thereby compensated for and speed variation prevented, this, however, with cumulative series winding, only holding good for inductive loads, *i.e.* lagging current.

In another method sometimes used, the compensation at the converter field is brought about by the change in the wattless component of the load current, thus preventing instead of correcting speed variation. In addition to the ordinary field winding energised from the terminals of the machine, there is an auxiliary winding which is supplied from the commutator of a special exciter, coupled to the converter shaft. This has a field magnet system with no windings, and its armature, which is wound for the same number of poles as the converter, has both commutator and sliprings.

A transformer connected in series with the leads to the converter sliprings is so designed as to produce in its

secondary windings currents which are strictly proportional to the currents in the primary. These secondaries are connected to the slipring brushes of the exciter, so that the armature of the latter is traversed by the secondary currents and rotating magnetic fluxes are set up therein.

The rotation of the armature being at synchronous speed, these fluxes are stationary in space and the pressures self-induced in the armature conductors appear on the commutator, as explained when dealing with self-starting converters.

The armature is rotating synchronously with the pressure at the converter sliprings, so that any displacement between the current and pressure at the converter will cause a corresponding displacement in space of the flux in the exciter armature.

If the current lags the armature will have travelled further before current maximum occurs and the flux will be displaced forwards, while the opposite effect obtains with leading current. The points on the exciter commutator between which maximum pressure exists will have a position in space depending on the phase relationship between current and pressure in the converter.

The exciter brushes are placed so that when the power factor of the converter is unity, they are midway between these points of maximum pressure, and the terminal pressure of the exciter therefore zero, no current flowing in the auxiliary winding on the converter field magnets.

If the current becomes displaced from the pressure the exciter armature flux shifts and a pressure appears between the brushes, a current then flowing in the auxiliary winding. This is so connected as to strengthen the main flux when the current lags, so compensating for the demagnetising effect of the lagging armature current.

If the current leads, the exciter flux shifts in the opposite

direction and the exciter brushes become of opposite polarity, the current in the auxiliary winding then weakening the main flux.

Any change in the armature reaction on the converter field, whether due to changing power factor or to varying load with constant power factor, is compensated for by this means and fluctuations of speed are prevented, for it will be observed that it does not require a variation of speed to bring about the effect.

The action of the exciter will be seen to be exactly similar to that of the converter, with regard to effect of armature currents on its own field magnets.

**Inverted Converters in Parallel with Synchronous Generators.**—When converters are running inverted in parallel with other synchronous generators variation of the field current affects both the load and the power factor. For example, the effect of weakening the field, by its tendency to cause a rise in speed, will be to advance the pressure wave of the converter relatively to that of the other generators, until sufficient extra load is taken to balance the extra c.c. input consequent on such reduction of the back e.m.f.

In addition to this a resultant pressure will arise between the machines which will introduce a leading component into the current in the converter, so changing the power factor of this machine, raising it if already lagging.

As this leading component tends to strengthen the field of the converter, both effects, load and power factor variation, are modified to some extent.

If the machine has already a lagging current this will be exerting a weakening effect on the field, which effect will be reduced by the introduction of the leading component.

The provision of extra reactance on the a.c. side for

the purpose of pressure control when running straight, is a disadvantage when running inverted and alone.

The power factor of a single machine supplying a load is determined by the nature of that load and cannot be changed by field regulation.

With reactance, the pressure of the supply will be reduced with inductive loads, while with leading power factor the pressure will be boosted, exactly as when the converter is running straight and represents the load supplied from the a.c. system. The only effect, then, is that any variation in the power factor of the load will vary the pressure, making the regulation of the machine coarser.

For this reason, a converter required to run either straight or inverted and having reactance control, should have the reactance arranged so that it may be short-circuited or cut out when running inverted, if no other synchronous generators are in parallel.

When such plant is in parallel the reactance is useful, as if the field be weakened, the leading current so arising boosts the pressure and partly compensates for the reduction in machine terminal pressure, thus restricting the leading current.

Field variation, then, has a greater effect on the load and less on the power factor of the machine.

Converters with synchronous boosters, when run inverted, have their operation greatly facilitated.

The load may be adjusted by the converter field and the power factor by that of the booster. In general if the converter field be weakened to pick up load, the booster field must be increased to maintain the power factor constant, and vice versa.

Boosting thus has an adverse effect on the commutation as in straight running, the booster acting as generator

or motor, and being driven by, or driving the converter exactly as in straight running.

### BALANCING ON 3-WIRE SYSTEMS

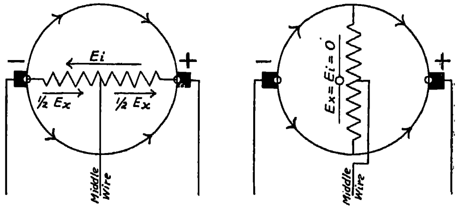
In a 3-wire c.c. system supplied by rotary converters, balancing of the pressures between the outers and the middle wire may be very simply effected by applying the principle of the static balancer to the transformers on the a.c. side of the converter. In order to understand how this is done it will be useful to consider first the static balancer as a separate piece of apparatus, after which the suitability of the power transformer for this duty will be easily seen.

If two tappings 180 degrees apart in the armature winding are connected to the two ends of a choking coil, this coil will be subjected to an alternating pressure having a maximum value equal to the continuous pressure at the commutator brushes. If we ignore the very low resistance of the coil and the small losses which occur, the reactive pressure set up by the magnetising current may be considered, for all practical purposes, as in opposition to the impressed pressure and of equal value. When the tappings coincide with the commutator brush positions, then, the impressed pressure will be from the positive end of the coil towards the negative, and the reactive pressure in the opposite direction. From the middle point of the coil to either end the reactive pressure will be that due to one-half of the total number of turns, or one-half of the commutator pressure.

This position corresponds to Fig. 45 (*a*), where the arrows on the circle indicate the direction of the pressure generated in the winding, $E_i$ the pressure impressed on the choking coil, and $E_x$ the reactive pressure in opposition.

From either brush to the middle point of the coil (to which the middle wire is shown connected) there is a pressure equal to one-half of that between the outers on the c.c. side. Considering also the indirect path from one brush through the armature to the opposite end of the coil and so to the middle wire this still holds good, there being in this path the full armature pressure minus one-half the reactive pressure in opposition, the resultant therefore being one-half the full pressure.

In (*b*) is shown the position when the tappings have




(a) (b)

Fig. 45.

moved 90 degrees and are midway between the brushes, the impressed and reactive pressures in the coil being now zero. Between the middle wire and the commutator brushes, however, there is still one-half of the outech pressure, owing to one-half of an active section of armature winding being included in the paths, is more direction. At other positions of the tappingsion of the pressures, that due to the winding and thaing with the reactive e.m.f. of the coil, combine so tha brushes. With is always equal to one-half of that betwey lead to sparking brushes. of the armature.

The curves in Fig. 46 represent the changes in these pressures between the middle wire and one of the commutator brushes, one end only of the coil being considered during the progress of the armature through two pole pitches (360 degrees).

At (*a*) the tapping coincides with the brush position

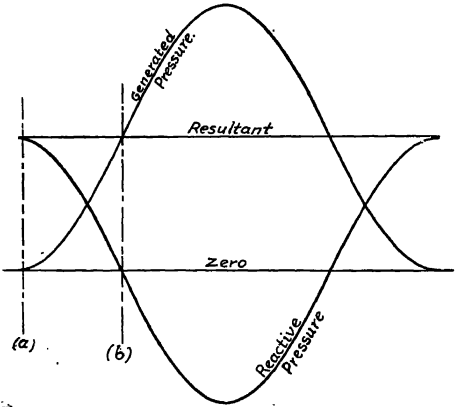



Fig. 46.

tı
oppo
either
half of tıactive conductors are in circuit, the pressure from commutator being therefore zero ; the reactive pressure in

This positio owever, at maximum, and from the middle arrows on the circ half of the commutator pressure. As the generated in the wi active conductors begin to be included the choking coil, and $E_x$ the brush, and their e.m.fs. are thus

thrown into the middle wire circuit as shown by the curve rising, until at (*b*) the pressure from this source has reached one-half of its maximum value. Meanwhile, the reactive pressure in the coil has fallen to the point of reversal, or zero. (Compare also (*a*) and (*b*), Fig. 45.)

Further movement of the armature brings more active conductors in until, when the opposite brush is reached, the full armature pressure exists between the middle wire and the brush taken for our starting point; this is partly cancelled, however, by the reactive pressure which has risen to its maximum in the opposite direction.

The resultant of the two curves is seen to be a horizontal line having a height equal to one-half of the maximum of the curve of generated pressure, and this applies equally to either half of the choking coil and with reference to either of the commutator brushes.

By connecting the middle wire of the c.c. system to the middle point of the choking coil the pressures on either side may be kept in balance, and any difference in the loads connected will result in a larger current in one or other of the outers, the out of balance current flowing to or from the generator over the middle wire, according to whether the greater load is on the positive or negative side. The out of balance current will always be in opposite directions in the two halves of the coil, flowing continuously from or to the middle wire, and will therefore have no effect on the magnetisation of the core, the m.m.fs. opposing each other.

With unbalanced loads one set of brushes is more heavily loaded than the other, and the distribution of the current in the armature is not uniform, varying with the position of the tappings with respect to the brushes. With a large degree of out of balance this may lead to sparking at the brushes and unequal heating of the armature.

Commutation is assisted by arranging the interpole windings so that each pole carries two coils, one connected on the positive and one on the negative side of the machine, the commutating flux then being affected by out of balance on either side. This is only a partial remedy, as of the conductors undergoing commutation at any instant, the top and bottom layers are connected to commutator bars under brushes of opposite sign.

The inequality of currents in the armature conductors is reduced by having more than one balancing coil, additional coils being connected to the winding at points spaced equidistant from the first pair of tappings. Two coils at 90 degrees may be used with the middle wire connected to the middle of each, giving four paths for the out-of-balance current; or three coils having only one end of each taken to a tapping, these being spaced 120 degrees apart, while their other ends are grouped at the middle wire.

The latter arrangement has the advantage of only requiring three sliprings as against four for 90 degree coils.

The amount of out of balance which can be dealt with by the static balancer is limited by the considerations mentioned above, and is usually stated as up to 25 per cent. of the full rating of the generator.

Static balancers for c.c. generators resemble in form and construction the ordinary a.c. transformer.

Power transformers for supplying rotary converters may be used as static balancers in addition to their ordinary duty by connecting the middle wire of the c.c. system to a suitable point in their windings. Such a point would be the star point of a 3- or 6-phase star, or of a 4-phase star where the supply is 2-phase, while with diametrically connected transformers the middle point of one phase may be used.

A low-pressure alternator supplying converters may have the middle wire taken to the star point of its windings. Where transformers are mesh connected a suitable point is not available, and a separate static balancer must be used as with ordinary c.c. generators on this system.

## CHAPTER XIV

### *TRANSFORMER CONNECTIONS*

**General Principles of the Transformer.**—It is scarcely possible to deal at any length with the rotary converter without making some reference to transformers. The necessity for an alternating pressure having a certain ratio to the continuous pressure required, and the fact that in practically all cases the working pressure is settled by considerations other than those of any rotary converters in an a.c. system, renders the employment of transformers in combination with rotary converters almost inevitable.

A preliminary conversion of the a.c. energy in addition to transformation of the pressure is often effected by means of the same piece of apparatus, so as to enable more efficient types of rotary converter to be used for the final conversion to c.c., as, for example, 3-phase to 6-phase, and 2-phase to 3- or 6-phase. A brief account will therefore be given of the principles involved in the transformation of alternating pressures, and of the various arrangements of connections necessary for different systems of low-pressure supply to rotary converters.

In its simplest form the transformer consists of two coils, the primary and the secondary, so arranged on a laminated iron core that the flux set up by a current in one coil links with the other. When an alternating current flows in the primary an alternating flux is set up in the core,

and this in addition to producing a reactive pressure in the primary coil by self-induction, also produces a like pressure in the secondary coil by what is known as mutual induction. If all the flux links with both coils the e.m.f. induced per turn will be the same in each, and further, both e.m.fs. will be in the same direction round the core at any instant.

When the supply pressure is applied to the primary with the secondary on open circuit, the primary acts as a choking coil, passing only a comparatively small current. This current can be divided into two components, one, the magnetising component, lagging by 90 degrees, and the other a power component in phase with the pressure and supplying certain losses in the iron core. As the former is much the larger of the two the angle of lag of the actual current will be large, approaching 90 degrees, and the no-load power factor of the transformer very low.

The flux is in phase with the magnetising component, and the reactive pressure, lagging by 90 degrees from the flux, will be in opposition to the primary pressure and may be considered as equal in value, turn for turn.

If the secondary winding has the same number of turns as the primary the pressure induced therein will accordingly be equal to the reactive pressure, and therefore to the primary pressure. Furthermore, it will have the same phase relationship to the primary pressure, being in the opposite direction to the latter round the core, at any instant. With a secondary winding having more or fewer turns than the primary the number of linkages of the flux will be greater or less, and consequently the secondary pressure will have a higher or lower value for a given primary pressure. The pressure is said to be "stepped up" or "stepped down" according to whether the secondary pressure is higher or lower than the primary.

If the secondary winding is connected to a closed external circuit a current will flow therein, the value of the current depending on the secondary pressure and the impedance of the circuit. This current flowing in the secondary winding will produce an m.m.f. in opposition to that of the primary, tending to reduce the total flux in the core. This, however, will lessen the reactance of the primary winding and bring about an increase of the current therein until the flux is restored to its former value.

Now the effect of the secondary m.m.f. can only be neutralised by an equal primary m.m.f. in opposition. The primary and secondary load currents, then, will be in phase opposition, and their values will be inversely proportional to the number of turns in their respective coils. In a step-down transformer, for example, the m.m.f. of the current in the secondary with fewer turns will be balanced by the m.m.f. of a smaller current in the larger number of turns in the primary coil. Thus with the step-down of pressure there is a step-up of the current in proportion, or in other words, the watts input equals the watts output, if internal losses are ignored.

The actual current in the primary will be the resultant of the no-load current and the load current required to balance the ampere-turns of the secondary load current. The power factor of the primary circuit will be dependent on that of the secondary, being modified in addition by the wattless, or magnetising component of the no-load current. This lags by 90 degrees, so that, broadly speaking, with a lagging current in the secondary the lag of the primary will be greater, while with a leading secondary the lead of the primary will be less.

For the complete study of the action of the transformer many other considerations have to be taken into account, the discussion of which is not necessary here. Enough has

been said, however, to indicate the manner in which the secondary pressure is obtained, and how an increased demand by the secondary circuit is met by increased input to the primary.

**Transformer Tappings.**—Different values of the secondary pressure for a given primary pressure may be obtained by making connection to the windings at different points by tappings, so as to include a greater or lesser number of turns in the circuit. These may be made to either of the two windings, reducing the number of active turns in the primary having the same effect as increasing those in the secondary, and vice versa. Where alterations are required only at infrequent intervals, this is sometimes done by unbolting the connections and shifting them to the new positions. When frequent changes are required, tapping switches on the transformer are used, some arrangements being only suitable for operation when the transformer is dead, while others allow of the alteration being made while on load, if so desired.

Transformers for tap-started rotary converters have the tapping connections brought to switches on the starting panel, as noted in the section dealing with these machines.

**Single and Polyphase Transformers.**—The simplest transformer is that for single-phase supply, in which there are only two windings and four terminals. For polyphase systems single-phase transformers may be used for each phase with their corresponding windings suitably connected, or a polyphase transformer having the different phases wound on separate limbs of a specially arranged core. With either arrangement the system of connections will be the same for a given desired result.

### 2-Phase Transformation

**2- to 2-Phase.**—Where the incoming high-pressure supply is 2-phase and a 2-phase converter is used, each primary will have its corresponding secondary, giving two low-pressure phases with 90 degrees displacement. Each of these is connected to tappings which are 180 degrees apart in the armature winding.

These connections are shown in Fig. 47, from which it will be seen that if the pressure in a given direction in

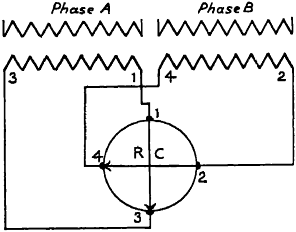



Fig. 47

phase A precedes that in B, the phase rotation at the converter terminals will be clockwise. That is, it will be in succession from 1 to 3, 2 to 4, 3 to 1, and 4 to 2 in the armature. By crossing over the leads from one of the secondaries the phase rotation will be reversed.

**2- to 3-Phase.**—The most widely known method of transformation from 2-phase to 3-phase or vice versa, is by means of the Scott connection. In this two single-phase transformers are used of which one, the "teaser" transformer, gives a secondary pressure equal to only 0·866 of that given by the other or "main" transformer.

One end of the teaser secondary is connected to the middle point of the main secondary as in Fig. 48.

Between terminals 1 and 3 there will be two sources of pressure, the teaser winding and one-half of the main secondary, with a 90 degree displacement. These two pressures having values of 0·866 and 0·5 their resultant will be equal to 1·0, or the pressure at the terminals of the main secondary. The same applies to terminals 2 and 3 with the difference that the section $A_2$ is reversed with respect to the teaser.

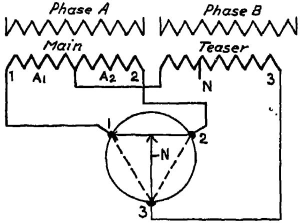



Fig. 48.

For example, if the pressure in phase A leads that in phase B, maximum of A from left to right in the diagram is followed by maximum of B in the same direction. Thus the pressure in $A_1$ towards terminal 3 leads that in the teaser by 90 degrees.

On the other hand, with the same order of precedence of the phases, maximum from left to right in $A_2$ is *away* from terminal 3, followed 90 degrees later by maximum in B *towards* 3. The pressure in $A_2$ therefore lags behind that in the teaser, while $A_1$ and $A_2$ are in opposition when considered with reference to terminal 3. These relations

are shown in the vector diagram in Fig. 46, where it will be seen that the result is to produce three equal pressures having a phase displacement of 120 degrees, thus forming a symmetrical 3-phase system. The point N in the teaser winding is the neutral point of the three phases, and may be used for 3-wire balancing. The number of turns between terminal 3 and N is two-thirds of those on the teaser, or 0·58 of the main winding.

When supplying a balanced 3-phase load, such as a rotary converter, the currents in the three line wires will be equal and will have a displacement from each other of 120 degrees. Considering each part of the transformer secondaries from the common junction between them, the currents in these must equal their respective line currents and therefore equal each other, and will have the same displacement between maxima in a given direction with reference to the junction point. In the main secondary these two currents in either half of the winding, while displaced by 120 degrees from each other with reference to the middle point, are only 60 degrees out of phase when the two halves are considered as in series with each other from one terminal to the other. For example, the successive maxima occur, say, towards the middle point, with an interval of 120 degrees, but these maxima are in opposite directions, considering the winding as a whole. That is to say, maxima in opposite directions occur at intervals of 120 degrees, consequently maxima in the same direction occur at 60 degrees.

The two halves of the winding will produce m.m.fs. differing in phase by 60 degrees and the resultant of the two will be equal to 1·73 times either of them, or 0·866 of the m.m.f. which would be produced if the currents in the winding were in phase with each other.

The teaser winding, carrying a current equal to that in

the main winding, and having only 0·866 of the number of turns in the latter, will produce an equal m.m.f. in its core. These m.m.fs. in the cores of the two transformers must be balanced by a corresponding m.m.f. produced by the current in the primary; thus the balanced 3-phase load on the secondary side is supplied equally from the two primary phases. The currents in the two halves of the secondary of the main transformer will be displaced by 30 degrees from the pressure between its terminals. This can be seen by considering that the main secondary pressure is displaced from that of the teaser by 90 degrees, whereas the 3-phase currents are displaced by 120 degrees, and the current in the teaser is in phase with its pressure. In one half of the main secondary, then, the current leads the pressure, and in the other half it lags; by 30 degrees in each case. The main transformer has, therefore, an internal power factor of 0·866 on the secondary side, while the power factor of the teaser secondary is unity.

The watts output on the secondary side of each transformer are equal when the load is a balanced one, the value at the teaser being found by 0·866 × 3-phase line pressure × line current, and at the main transformer by 3-phase line pressure × line current × p.f. 0·866.

**3- to 2-Phase.**—Scott-connected groups are also used in which the 3-phase side is the primary and the 2-phase side the secondary. These may be found where an original 2-phase supply has been superseded by 3-phase, their use enabling the existing 2-phase converters to be run from the new supply.

When balanced 3-phase pressures are applied to the primary windings of such a group, the currents which flow produce m.m.fs. in the cores in the same manner as the 3-phase secondary load currents, dealt with in the preceding section, and the pressures in the two secondary

phases arise in consequence of the fluxes set up by these m.m.fs.

When load currents flow in the secondary windings opposing m.m.fs. are produced in the cores, these being balanced by increased currents on the primary side. The previous remarks as to internal power factor and to calculating the watts on the 3-phase side apply also in this case.

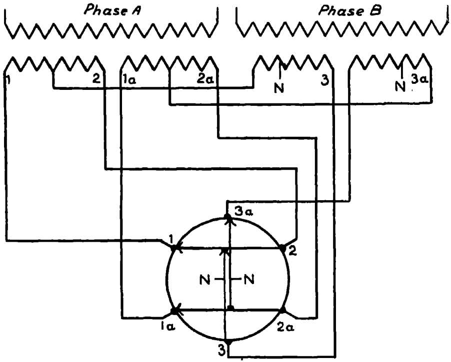



Fig. 49.

**2- to 6-Phase.**—By a duplication of the Scott connection a 6-phase converter may be run from a 2-phase supply. Four transformers may be used having a single primary and secondary each, or instead, two transformers each having one primary and two secondaries. The secondaries are connected as shown in Fig. 49 and produce two 3-phase systems with the same direction of phase

rotation, while any two phases which reach maximum at the same instant are mutually opposing in the converter armature R.C. In the vector diagram the lines representing the teaser pressures are shown separated. Actually they should be in line, but if so shown would not indicate the make-up of the diagram so clearly. It will be observed that the neutral points N coincide in the diagram, indicating that there is no pressure difference between them. For the purpose of 3-wire c.c. balancing it is usually only necessary to connect the middle wire to one of these, although both may be used if the out-of-balance current to be dealt with is heavy compared with the load rating of the transformers.

## 3-Phase to 3-Phase.

**Delta Connection.**—Transformers for stepping down an incoming 3-phase supply to rotary converters may have their windings connected in three different ways on both primary and secondary sides.

In one method the three windings are connected end to end so as to form a closed circuit, the line wires being connected to the three junction points, each line wire being therefore common to two phases of the windings. This is known as the mesh or delta connection from the form it takes when represented by a vector diagram as in Fig. 50 (*a*), this resembling the Greek letter Δ (delta).

The pressure in each phase being displaced 120 degrees from that in its neighbours the resultant round the mesh is zero. The pressure between lines will be equal to that of one phase, while the line current will be the resultant of the currents in two adjacent phases. These phase currents although displaced by 120 degrees, when considering a given direction round the delta, are only displaced by

60 degrees in the line wire, as opposite directions in the phases give a common direction in the line wire. The line current, then, is equal to 1·73 times the phase current, or conversely the phase current equals 0·58 times that in the line.

It will probably have occurred to the reader that the armature winding of a 3-phase rotary converter is, in effect, delta-connected to the supply, the relations between phase and line pressures and currents being identical in each case.

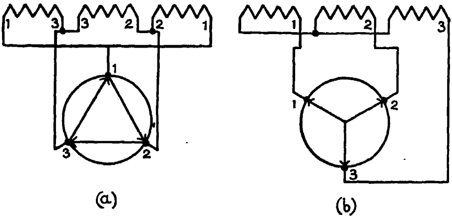



Fig. 50.

**Star Connection.**—The second method of connecting three phases consists of grouping all three windings together at one end and joining their other ends to separate line wires; this is called the star or Y connection and is shown in Fig. 50 (*b*).

When balanced 3-phase pressures are applied to a group of star-connected primary windings, assuming the reactances of these are equal, equal currents will flow in the line wires and these currents will have a displacement of 120 degrees between maxima in a given direction with reference to the common junction, or star point of the

windings. This being so, the total current flowing towards the star point is at any instant equal to the current flowing away from it. The reactive pressures induced in the windings will be practically equal to the impressed pressures, but it is to be observed that the latter is a pressure between lines, whereas the path between any two line wires is made up of two phases in series, the currents therein, and consequently the reactive pressures, being out of phase with each other. Now these phase currents and pressures are only displaced by 120 degrees when considered with reference to the star point. Pressures acting towards the star point are in opposite directions in the two phases when considering these as in series between two line wires; from this point of view, then, maxima in a given direction from one terminal to another have a phase angle of 60 degrees. The reactive pressure between two line terminals is the resultant of two phase pressures with 60 degrees between them, and has a value of 1·73 times that of either of them. Conversely, the phase pressure is equal to 0·58 of the line pressure.

The same thing applies to star-connected secondaries, where two phase pressures with 60 degrees displacement produce a line pressure of 1·73 times their value. The phase current obviously is equal to the line current.

From the values of line pressure and current as shown on switchboard instruments the total watts are calculated by the same method irrespective of whether the load is connected in delta or in star. In delta the phase current is 0·58 of that in the line, while line and phase pressures are equal; in star the phase pressure is 0·58 of that between lines, while line and phase currents are equal. In each case the expression 0·58 $\times$ line pressure $\times$ line current gives the watts per phase, and multiplying this by three we get 1·73 $\times$ line pressure $\times$ line current for the total watts.

**Inter-connected Star Connection.**—When star-connected secondaries are used to supply rotary converters for a 3-wire c.c. system, the middle wire of the latter may be connected to the star point of the transformers, as noted in the section on the static balancer. The out-of-balance current then flows equally and continuously through each phase of the secondary winding.

In 3-phase transformers of the core type, in which the core consists of three limbs united at each end by cross yokes, each limb carrying the windings of one phase, the m.m.fs. due to the continuous current all act in one direction from one yoke to the other. Any flux due to this m.m.f. can therefore only complete its circuit by leaving the core and passing through the air, so returning to the other end of the core.

The effect of the continuous current upon the magnetisation of the cores is consequently very small, owing to the high reluctance of the path through the air, unless this reluctance is reduced by the presence of iron in the vicinity, such as, for instance, the sides of the tank in which the transformer may be housed.

With shell-type transformers, on the other hand, the iron of the cores forms a continuous path round the outsides of the windings as well as the limbs passing through them. In these the out-of-balance current will set up a continuous flux in one direction which will be superposed on the alternating flux and so interfere with the proper working of the transformer. The same thing occurs if the 3-phase group consists of single-phase transformers of either type, a complete iron path existing for the continuous flux in each, with the same result.

In these circumstances a different method of connecting the secondary windings is adopted, this being known as the inter-connected star. The windings on each limb of

the core are divided into two equal sections, and one section on one limb is connected in series with another section on one of the other limbs, each pair so formed constituting one leg of the inter-connected star. As the alternating fluxes in the separate limbs (or separate cores in the case of three single-phase transformers) are out of phase with each other, the result of the inter-connection is to produce between the star point and the line terminal a pressure which is the resultant of those in the two half-phases.

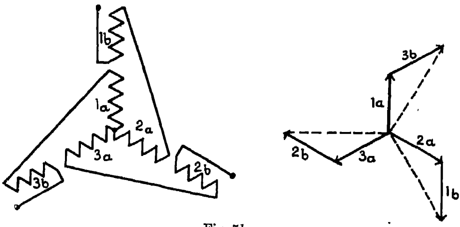



Fig. 51.

The arrangement of connections is shown in Fig. 51, with a vector diagram to indicate the proportions and phase angles of the various pressures. In this figure the windings on each core are shown separated by an angle equal to the phase displacement of the fluxes in the cores, as this presents a clearer picture of the relations between the pressures induced in the windings. This plan is often followed with transformer diagrams, as it produces a sort of combined connection and vector diagram.

Of each pair of half-phases in series with each other, it will be noticed that one is connected up in the reverse

direction to the other, the effect of this being to change the phase angle between the two pressures from 120 degrees to 60 degrees. The resultant pressure between star point and line terminal is therefore 1·73 times that of one half-phase, or 0·866 of that which would be produced if the whole winding were connected in plain star. The three resultant pressures thus produced are seen to have a displacement of 120 degrees from each other, and the pressures between line terminals bear the same ratio to the phase pressure as do those of a plain star system.

When an out-of-balance continuous current is being carried, the interconnection of the phases ensures that on each limb of the core the separate half-windings are carrying equal current in opposite directions. The continuous m.m.fs. are therefore mutually opposing and the alternating flux is undisturbed.

### 3-Phase to 6-Phase

**Double-delta Connection.**—In the double-delta arrangement the secondaries are connected so as to produce two deltas having similar phase rotation but with the pressures in corresponding phases displaced by 180 degrees. The necessity for the latter requirement can perhaps best be explained by inverting the problem, and considering the pressures generated in the armature winding of a two-pole converter, represented by the circle in Fig. 52. The numbered points are the tappings and the arrowheads indicate the direction of the generated pressure.

At the particular instant shown, the pressure between tappings 2 and 6, and also that between 3 and 5, is at maximum, but whereas the first is in a clockwise direction in the delta 2–4–6, the latter is anti-clockwise in its delta 1–3–5. The same thing occurs with the other pairs of

tappings when they reach maximum, so that the pressures between 120 degree tappings may be divided into two delta groups, reversed with respect to each other, but with similar phase rotation.

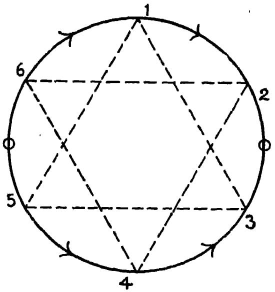



Fig. 52.

A double-delta system to be paralleled with this must have similar characteristics, and can be produced by the arrangement of transformer connections shown in Fig. 53, where the two deltas are kept separate to enable them to be more easily traced. Pairs of pressures, such as 6–2 and 5–3, which reach maximum simultaneously, are derived from one phase of the primary supply, 2–4 and 1–5 from the second, and 4–6 and 1–3 from the third primary phase, as indicated by the letters A, B, and C.

The primaries may be connected in either delta, star, or inter-connected star, this being decided by other considerations. It is only necessary for the 3- to 6-phase conversion that if separate transformers are used for each

secondary delta, both primary groups should be connected up alike.

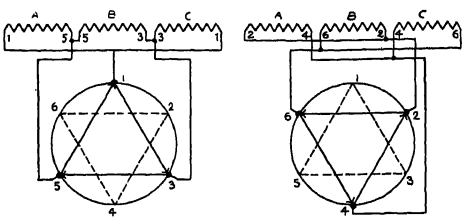



Fig. 53.

With double-delta connections, there is no neutral point available at the transformers for c.c. 3-wire balancing.

**Double-star Connection.**—In the double star arrangement six secondaries, two to each primary phase, are connected so as to form two 3-phase star groups, with 180 degrees between them and with similar phase rotation. The result is to produce two groups of 3-phase line pressures which may be paralleled with the corresponding pressures in a 6-phase converter. The connections are shown in Fig. 54, where line wires of the two stars are distinguished by full and broken lines respectively. It will be noticed that the two star points coincide in the diagram, indicating that there is no difference of pressure between them, so that they may be joined together, forming a 6-phase star. For 3-wire balancing the middle wire of the c.c. system may be connected to this star point.

Considering the 6-phase star, each pair of secondaries may be treated as being in series and connected to tappings 180 degrees apart, in the converter armature, as 1–4, 3–6, and 5–2. Furthermore, of each pair of secondaries, at

any instant one will be carrying current towards and the other away from the star point, and these currents will be equal. The necessity therefore no longer exists for

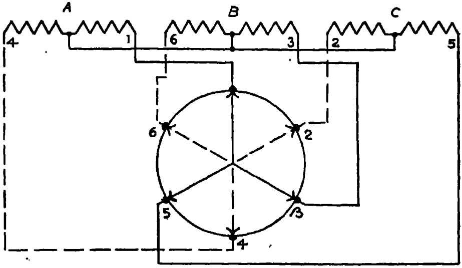



Fig. 54.

the star connection between separate pairs of phases, and thus the diametrical system of secondary connections is arrived at.

**Diametrical Connection.**—In this there is only one secondary to each primary phase. The three secondaries have a displacement of 120 degrees between their pressures, and each is connected between 180 degree tappings in the armature winding, as in Fig. 55. The correct phase rotation is obtained by connecting the corresponding end of each secondary to tappings 120 degrees apart. Thus in Fig. 55, if the maximum pressure occurs from left to right in the secondaries in the order A.B.C., terminals 1, 3, and 5 will become positive at successive intervals of 120 degrees, and rotation of phases in the vector diagram will be clockwise.

Alternatively, the diagram may be considered as representing the armature of the converter, when if the neutral

points are assumed to be on a vertical line through the centre, phase A will be at maximum in the position shown. After 60 degrees of rotation in an anti-clockwise direction, tappings 2 and 5 will be in the maximum position, but it will be observed that the pressure will now be in the opposite direction in phase C, as compared to that in phase A in the first position. Continuing thus, we find that maximum in a given direction in the phases occurs at intervals of 120 degrees in the order A.B.C. The conditions are there-

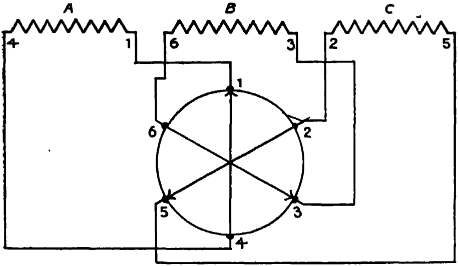



Fig. 55.

fore correct for paralleling with a 3-phase supply having the same phase rotation in the transformers.

The diametrical system of connections is that most commonly used for 6-phase converters. It has the advantage, which has been already referred to in connection with starting methods, of requiring only one 3-pole switch to interrupt the supply to the converter. With double-delta or double-star connections all six line wires must be broken or complete circuits will remain. It is usual in these cases to provide two 3-pole switches, one of them

being closed when the converter has been synchronised, the machine then running 3-phase on one delta or one star until the other switch is closed.

The middle wire of a 3-wire c.c. system is connected to the middle point of one phase only of diametrical secondaries, as otherwise a 6-phase star would be formed.

**Phase Pressures and Currents in 6-Phase Systems.**—Whatever the manner in which the transformers are connected, the result is always the same at the converter, the armature of which is connected as a 6-phase mesh to the six line wires. In each system, too, the line current for a given load is the same, as demonstrated when dealing with the 6-phase machine in Chapter VI.

The value of the pressure required from transformer secondaries depends on the continuous pressure required from the converter, and also on the system of connections used. With double delta, the pressure of one phase, equalling the line pressure of one delta, is to be that between 120 degree tappings, or 0·612 of the continuous pressure. With double star, the points of one star are also connected between 120 degree tappings, and require 0·612 of the continuous pressure between them, this being the line pressure of the star. The phase pressure will be 0·58 of the line pressure and therefore will equal 0·354 of the continuous pressure.

The pressure in one diametrical phase will be the sum of two star phases in series, or 0·707 of the continuous pressure, and the foregoing all being R.M.S. values, the maximum of the diametrical pressure will equal the continuous pressure, which accords with the fact of its connection between tappings 180 degrees apart.

The phase currents in the transformer secondaries also depend on the system of connections. In diametrical and double star the phase current is obviously equal to the line

current, while with delta connections, the current in each phase is 0·58 of that in the line.

**Switching out Transformers.**—Transformer windings are highly inductive on account of their iron cores, and when the magnetising current is switched off, the rapid collapse of the flux may cause the induction of pressures much in excess of the normal working value. This can be avoided when switching out transformers supplying rotary converters by opening the switch on the primary side first, to shut the machine down, leaving the switches in the secondary circuits closed. The flux is then maintained by currents from the converter armature, and as these die down with the decreasing speed of the machine, the flux is reduced gradually.

Although provision is always made for abnormal pressure rises when designing the insulation of transformers, yet it is better to avoid creating conditions wherein such rises occur, whenever possible: for this reason the foregoing procedure should always be followed when shutting down rotary converters.

## CHAPTER XV

### *THE MOTOR CONVERTER*

THE motor converter consists of two machines in combination, an induction motor and a c.c. generator, the rotor of the one and the armature of the other being mounted on the same shaft. In addition, the windings of rotor and armature are connected together, the leads for this purpose, in machines with a centre bearing, being carried through the hollowed-out shaft. These two machines are known as a.c. end and c.c. end respectively. In Fig. 56 is shown the general scheme of rotor and armature connections for a converter having one pair of poles at each end. The special arrangement at the star point of the rotor windings is for starting, and is explained in the section of this chapter relating thereto.

Considering the a.c. end first, this has its stator winding arranged in the usual manner, in accordance with the number of phases in the supply system, so as to produce a rotating field when energised. The rotor, of the same number of poles as the stator, has its winding divided into a number of phases, usually twelve, spaced equally, so that as the rotating field sweeps over it e.m.fs. are induced in the successive phases in turn at intervals of 30 degrees. These twelve phases are all connected together at one end, forming a star, the pressure between any two of the free ends of the star then being the resultant of

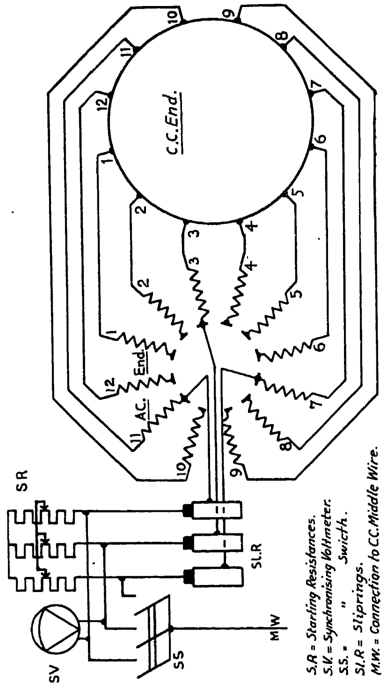

C.C. End.
A.C. End.
1
2
3
4
5
6
7
8
9
10
11
12
S R
Sl.R
SV
SS
M W
S.R = Starting Resistances.
S.V. = Synchronising Voltmeter.
S.S. = " Switch.
Sl.R = Sliprings.
M.W. = Connection to C.C. Middle Wire.

Fig. 58.

the e.m.fs. induced in the two phases, having regard to the angle of displacement (see vector diagram, Fig. 57 (*a*)).

When the stator winding is energised with the rotor star thus on open circuit no current will flow in the latter, and the frequency of the 12-phase pressures will be equal to that of the supply. If, however, the ends of the star are joined by resistances forming a 12-phase mesh, currents will circulate therein, and assuming for the moment that the rotor is fixed immovably, and neglecting losses, the whole of the energy input to the stator, or primary, will reappear in the rotor, or secondary winding, the machine

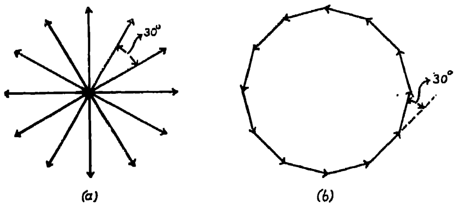



Fig. 57.

then acting simply as a transformer. With the rotor free to move, the interaction between the flux and the rotor currents causes it to revolve, part of the input now being converted into mechanical form. As the rotor runs in the same direction as the stator flux the relative motion between them is reduced, and the frequency and value of the rotor e.m.fs. decreases.

The machine is now acting as motor and transformer, converting its input partly into mechanical and partly into electrical form, the proportions in which the two conversions are carried out depending on the relative

speeds of the rotor and the stator flux. With the rotor at standstill the electrical conversion is a maximum and the mechanical conversion zero. As the rotor speed rises the electrical conversion falls off and the mechanical conversion increases until, if it were possible for the rotor to attain the full speed of the flux, the conditions would be the reverse of those at standstill, the whole of the input being converted into mechanical form.

The difference between the speeds of the primary flux and the rotor is known as the slip, and is the relative motion between the two, the rate of rotation of the flux round the rotor being reduced by the motion of the latter in the same direction. If the slip in revolutions per second is multiplied by the number of pairs of poles in the field the product is the slip frequency. This is the frequency of the e.m.fs. induced in the rotor, and it will be clear that with the rotor stationary the slip is equal to the stator flux speed, and the slip frequency will equal that of the supply, while as the rotor speed rises the slip frequency is reduced.

Thus if $f$=frequency of supply,
$fs$=frequency of slip,
$\mathrm{P}a$=number of pairs of poles in stator,
N=revs. per second of rotor,

speed of rotating flux$=\frac{f}{\mathrm{P}a}$ revs. per second,

$$\text{the slip}=\frac{f}{\mathrm{P}a}-\mathrm{N}$$

and multiplying this by $\mathrm{P}a$ we get

$$f-n\times \mathrm{P}a=fs \quad . \quad . \quad . \quad . \quad . \quad (1)$$

It should be noted that as the stator flux is moving faster than the rotor, the phase rotation in the rotor windings runs in a forward direction, keeping pace with the flux.

Turning now to the c.c. end, the armature of this

machine has tappings corresponding in number per pair of poles to the phases in the a.c. rotor. When the machine is running with the field magnets excited alternating pressures exist between these tappings, with a frequency depending on the speed and the number of pairs of poles in the field (see Fig. 57 (*b*)).

Thus if $fc$=frequency at c.c. end,
$Pc$=number of pairs of poles at c.c. end,
N=revs. per second of armature,

$$fc = N \times Pc \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Both a.c. and c.c. ends, therefore, produce a 12-phase group of pressures having this difference, that as the speed rises the frequency from the a.c. end falls, while that from the c.c. end increases. At a certain speed the two frequencies become equal, and provided that the interconnections are correctly arranged and the pressures equal, the two windings, on rotor and armature, may be connected together. The interconnections must be so disposed that the phase rotation runs in opposite directions in each machine. That is, taking each group of pressures separately and ignoring the other, the phase rotation produced in the c.c. armature by the rotor pressures must run backwards, while the phase rotation produced in the rotor windings by the c.c. armature pressures must run forwards with respect to the rotation of the machine. Then when the two frequencies are equal, the motion of the armature keeps the phase rotation therein stationary with respect to the field, while the forward phase rotation in the a.c. rotor has added to it the rotational speed of the machine, thus being kept in step with the primary field.

The frequency of the rotor pressures being that of slip, the frequency of the c.c. end must also be that of slip for

synchronism, and the speed at which this occurs depends on the numbers of poles in the two machines.

Thus for synchronism $fs = fc$; using the expressions found above for these two frequencies,

$$f - N \times Pa = N \times Pc \quad . \quad . \quad (1) \text{ and } (2)$$

$$f = N(Pa + Pc)$$

and

$$N = \frac{f}{Pa + Pc} \quad . \quad . \quad . \quad . \quad (3)$$

Therefore the speed in revs. per second at which the frequencies of both ends are equal is found by dividing the supply frequency by the sum of the pairs of poles in the two machines. It can be seen from equation (3) that if both ends have the same number of poles the speed of the rotor will be half that of the rotating field, and the rotor frequency will be one-half that of the supply.

The question of the actual means employed in practice for starting and synchronising is dealt with later; we go on now to consider the action of the machine when synchronism has been obtained.

If the machine were running in synchronism and with absolutely no losses, the alternating pressures from both ends would be exactly in opposition and no current would flow in the rotor system; there would therefore be no torque at either end. Actually, of course, there are frictional and other losses to be met so that the rotor tends to drop from synchronous speed, and as a change in speed affects the two frequencies in opposite ways, the pressure from the a.c. end advances in phase while that from the c.c. end lags. The resultant pressure thereupon arising produces a current in the rotor circuits and this creates a motoring torque, not only in the c.c. end, but also in the a.c. end. The losses are then met by the a.c. end acting partly as induction motor, and partly as transformer

supplying energy to the c.c. end which operates as a synchronous motor. In addition, energy may be taken from the c.c. terminals of the machine, the c.c. end then acting partly as rotary converter, and partly as c.c. generator driven by the induction motor.

It will be observed that owing to the differential action of a change of speed on the relationship between the two pressures, the variation required to bring about a given effect is much less than would be the case in an ordinary synchronous motor. This is an important feature of the motor converter, it being practically impossible for these machines to lose synchronism, no matter how violent the load changes to which they may be subjected.

**Ratio of Mechanical and Electrical Conversions.**— With a given supply frequency the speed of the rotor when the two ends are in synchronism depends on the total number of poles in the two machines, but the proportion in which the primary input is converted into mechanical and electrical form in the rotor depends, with a given total number of poles, on the relation between the number of poles in each machine.

At synchronous speed the slip will depend on the number of pairs of poles in the a.c. end, and by making these a greater or lesser proportion of the total number, the ratio of electrical and mechanical conversion may be varied. The more nearly the rotor speed approaches that of the stator flux (that is, the smaller the slip) the greater is the proportion of the total input which is converted mechanically. With a given rotor speed, these become more nearly equal the larger the number of poles in the stator. Therefore, with a given total number of pairs of poles and supply frequency, the amount of the total input which is converted into mechanical energy is proportional to the number of pairs of poles in the a.c. end.

$$\text{Thus}\qquad \frac{\text{rotor speed}}{\text{stator flux speed}}=\frac{\dfrac{f}{Pa+Pc}}{\dfrac{f}{Pa}}=\frac{Pa}{Pa+Pc}$$

$$=\frac{\text{mechanical conversion}}{\text{total input}}$$

The greater the *difference* between the rotor speed and that of the flux, that is, the more nearly the slip frequency approaches the supply frequency, the greater the proportion of the input which is converted into electrical energy in the rotor. With a given rotor speed the slip frequency, which equals the frequency at the c.c. end, is proportional to the number of poles at that end. Therefore, with a given supply frequency and total number of pairs of poles, the energy converted electrically is proportional to the number of pairs of poles in the c.c. end.

$$\text{Thus}\qquad fs=\text{rotor speed}\times Pc$$

$$\text{and}\qquad \frac{\text{slip frequency}}{\text{supply frequency}}=\frac{\dfrac{f\times Pc}{Pa+Pc}}{f}=\frac{Pc}{Pa+Pc}$$

$$=\frac{\text{electrical conversion}}{\text{total input}}$$

In both the foregoing expressions the internal losses in the machine have been ignored.

**Pressures and Currents in Rotor and Armature.**—The windings of the rotor and armature must be designed to produce pressures having equal values, as they are to be connected together. Moreover, these pressures will have a fixed relation to the continuous pressure required from the machine, as in the rotary converter.

Considering first of all the relation between rotor and armature pressures, it is to be noted that the rotor windings

are connected in star, while the armature is a mesh. The pressure between two adjacent tappings in the armature will be that due to one phase of the mesh; the corresponding pressure in the rotor, or that between two points of the star, will be the resultant of the e.m.fs. induced in two star phases with a displacement of 30 degrees relative to the star point, and therefore of 30—180= 150 degrees when considered in series. This resultant will have a value of 0·518 of the pressure due to one star phase alone, or conversely, the star phase pressure will be 1·93 times the mesh pressure.

In the c.c. armature the pressure between tappings 180 degrees apart will equal 0·707 of the pressure between commutator brushes, and this will be twice that of one phase of the rotor star. The star-phase pressure will therefore be 0·354 of the continuous pressure, and 0·518 of this, or 0·183, will be the value of the mesh pressure in terms of that on the commutator. These values are tabulated herewith in terms of each other.

$$E_{mesh}=0{\cdot}518E_{star}=0{\cdot}183E_c$$
$$E_{star}=1{\cdot}93E_{mesh}=0{\cdot}354E_c$$
$$E_{dia.}=3{\cdot}86E_{mesh}=2{\cdot}0E_{star}=0{\cdot}707E_c$$

The current in the rotor for a given output from the c.c. side depends, of course, on the ratio of electrical conversion. Neglecting losses, the watts input or output multiplied by $\dfrac{Pc}{Pa+Pc}$ will give the watts in the rotor system. Dividing this by 12 gives the watts per phase, and again by the star pressure gives the current per phase in the rotor, which is the same as the current per tapping at the c.c. end. Each tapping carries the current from two of the armature phases 30 degrees apart, and as maxima in a common direction in the armature phases are in

opposite directions in the tappings, the tapping current is the resultant of two currents with 30—180 degrees, or 150 degrees between them. The phase current is therefore 1·93 times the current in the tapping, or conversely, the latter is 0·518 time the former.

Considering the watts in the rotor from the c.c. end, dividing by 12 gives the watts per phase of the mesh, and again by the mesh pressure (0·183 time the continuous pressure) gives the current per phase in the armature. The tapping current is equal to 0·518 of the mesh current, and this is the current per phase in the rotor star.

If the electrical input to the c.c. end were equal to the output (as in a 12-phase rotary converter) the current per tapping would equal 0·236 of the continuous current. In the motor converter the electrical input to the c.c. end is always less than the output in the ratio $\frac{Pc}{Pa+Pc}$, so that if $Ic$ be the continuous current, the current per tapping will be equal to $\frac{Ic \times Pc \times 0{\cdot}236}{Pa+Pc}$, assuming the power factor in the rotor to be unity, which is not always the case.

**Power Factor and Pressure Regulation.**—As the c.c. end is running as a synchronous machine its power factor depends on the field excitation. The current may be made to lead or lag by increasing or decreasing the field current, and this will react on the supply to the primary, or stator, of the a.c. end. The latter acting as a transformer will have the power factor of the primary dependent on that of the secondary, or rotor, and therefore may be made to take its energy from the supply at unity, or even leading power factor by suitably increasing the excitation at the c.c. end. If the rotor currents were exactly in phase with the pressure the primary current would still lag, on account of the magnetising component required for the rotating

flux. By making the rotor current lead, however, the magnetisation can be wholly maintained from the c.c. end, and the power factor of the a.c. input raised to unity or leading.

Such variation of the field strength, of course, affects the continuous pressure, and in general, it may be said that for any given value of the latter the power factor is fixed by the design. For lighting service machines are usually designed for unity power factor at full load, while compounded machines for traction work give unity at three-quarters load, and a leading power factor at full load.

The continuous pressure of a motor converter may be varied over a much wider range by field regulation than is possible with the rotary converter without unduly lowering the power factor of the supply. This arises from the fact that in the motor converter the electrical energy in the rotor is less than the total load on the machine; the increase in the kVA consequent on a change in the power factor in the rotor being thus smaller than would otherwise be the case. For example, in a motor converter with equal numbers of poles at both ends, the electrical energy in the rotor is one-half of the total input to the stator. A lowering of the power factor to 0·8 means an increase of the kVA in the rotor by 25 per cent., but this is only 12½ per cent. of the total input. A given variation in the power factor of the c.c. end produces, therefore, only one-half of the effect on the a.c. input that would be caused by a similar variation in a rotary converter.

The current on the a.c. side of the armature being smaller than would be required for the full input if in electrical form, the armature heating will be affected to a lesser extent by low-power factor. Furthermore, the effect on the field flux of the armature reaction due to current displacement is less; therefore there is a greater total effect produced

on the pressure generated by the machine. Thus, for a given field variation, the effect on the power factor of the supply is less, and the change in the pressure generated is greater, than would be the case with a rotary converter. It will be evident that the smaller the proportion of the total input which is converted into electrical form in the rotor, that is, the smaller the value of $\frac{Pc}{Pa+Pc}$, the greater the range of pressure control at the c.c. end for a given variation of power factor in the supply.

For the reasons outlined above motor converters require no additional apparatus to facilitate control of the continuous pressure, it being possible to get a variation up to 40 per cent. of the normal, in suitably designed machines, by simple field regulation.

The characteristics of shunt-excited motor converters are slightly drooping, so that they run quite stably in parallel with each other, or with rotary converters or c.c. generators. When compounded, equalising connections must, of course, be provided exactly as with compounded machines of other types.

**Starting and Synchronising.**—The most convenient a.c. arrangement for starting the motor converter, and the method always used, is to make the interconnections between rotor and armature of a permanent nature and to disconnect the rotor phases at the star point. This is done by bringing the inner ends of the twelve phases to a set of contacts which may be opened or closed by hand while the machine is running. When the star point is thus opened no current can flow in the windings, and the machine would be unable to start itself. Three of the phases, however, spaced 120 degrees apart, have their inner ends connected to sliprings also, the brushes on which are connected to a variable 3-phase resistance.

When the supply is switched on to the stator, currents circulate through the rotor and armature windings and the resistances, and the machine starts up as an induction motor, the speed being controlled by the amount of resistance in circuit.

The field circuit of the c.c. end is permanently connected to the machine terminals, and when the speed has risen slightly above synchronism, the pressure in the armature is allowed to build up, and combining with the rotor pressure, produces a resultant which pulsates at a rate equal to the difference between the two frequencies. This pulsation is shown on the voltmeter connected across the starting resistance, owing to the varying current therein. The set then begins to slow down, reducing the difference between the frequencies, the pulsations of the voltmeter getting slower as synchronism is approached. The resistances are short-circuited by closing a switch, at a moment when the slow swinging of the voltmeter shows nearly equal frequencies, and the bottom of a swing phase opposition of the pressures. Cutting out the resistances thus allows the full synchronising torque to come into play at any attempt to depart from synchronism, and the speed is kept at that value at which the frequencies of rotor and armature pressures are equal, by the interaction of the armature current and the c.c. field. The short-circuiting device is then closed, completing the star of twelve phases, after which the brushes may be lifted from the sliprings unless these are required for carrying the out-of-balance current from a 3-wire c.c. system.

The starting resistance and field regulator usually have marked positions found by the makers on test, which allow of the speed rising above synchronism before pulling down again. The operator has then only to close the main a.c. switch and wait until the correct moment for

short-circuiting the resistances, as shown by the voltmeter.

In the self-synchronising arrangement reactances are connected between the leads from the sliprings and controlled by a switch. As the machine approaches synchronous speed the reactances are switched in, and a larger current flowing in the rotor and armature brings the c.c. end into synchronism.

When starting up from the c.c. side the star point of the rotor windings is kept open until the set is under way, to avoid current circulating in the rotor windings and so increasing the input at starting. As the speed rises alternating pressures are impressed on the rotor windings by the back e.m.f. of the armature, and on the star point being closed currents flow in the rotor, producing a rotating field. As explained earlier, the inter-connections are so arranged that the pressures generated by the c.c. end produce forward phase rotation in the rotor windings of the a.c. end. The speed of the phase rotation relative to the rotor will be equal to the frequency of the armature pressures divided by the number of pairs of poles in the a.c. end, or

$$\frac{N \times Pc}{Pa}$$

This rotation being in a forwards direction will have added to it the speed of rotation of the rotor, so that the actual speed of the rotating field in the rotor relative to the stator will be equal to

$$\frac{N \times Pc}{Pa} + N = \frac{N(Pa + Pc)}{Pa}$$

This rotating field sweeping the stator windings will induce therein pressures having a frequency equal to the product of field speed and the number of pairs of poles

in the stator, or if $f_i$ is the frequency of the induced pressures

$$f_i = \frac{N(Pa+Pc)}{Pa} \times Pa = N(Pa+Pc)$$

Thus the frequency of the pressures induced in the a.c. stator is equal to that of a synchronous alternator having the same number of pairs of poles as the two ends of the converter combined. It will be observed that when the induced frequency equals that of the supply, N equals the speed at which the pressures in rotor and armature come into synchronism in starting up from the a.c. end (see equation (3) above).

Paralleling between the stator pressures and the a.c. system is carried out by means of ordinary synchronising apparatus.

**Inverted Running.**—If the machine is paralleled with other generating plant on both sides, the direction in which the transference of energy takes place depends on the pressure generated in the c.c. end and the phase relationship of converter and impressed pressures at the a.c. end. Assuming the conditions to be such that the losses are met by exactly equal inputs on both sides, the machine will operate as c.c. motor plus synchronous motor at the c.c. end, and as induction motor plus transformer at the a.c. end. If the c.c. field is strengthened the increased back e.m.f. reduces the c.c. input, the speed drops and the pressure lags on the a.c. side, which thereupon has its input increased. Further increase of field strength produces a load current in the armature, so causing increased input to the a.c. side to produce the extra torque required to maintain synchronous speed.

Weakening the c.c. field, on the other hand, by increasing the c.c. input advances the pressure on the a.c. side, so picking up load from the a.c. system. The c.c.

end acts as inverted rotary converter supplying energy to the rotor, which thus becomes the primary of the a.c. end, the stator windings now being the secondary. The currents in the stator being in the same direction as the induced pressure, a torque is created which opposes the relative motion between stator and rotor, so producing a load torque on the latter. The a.c. end therefore acts as an a.c. generator as well as a transformer, and a mechanical load is thereby imposed on the c.c. end, which acts as motor in addition to rotary converter.

The energy converted electrically is again proportional to the rotor frequency and therefore, with a given rotor speed, to the number of pairs of poles in the c.c. end, while the mechanical conversion is proportional to the number of pairs of poles in the a.c. end, as in "straight" running.

**3-wire Balancing**—For the purpose of balancing a 3-wire c.c. system the middle wire is taken to the star point of the rotor windings by means of the sliprings used for the starting phases. This star point is at a potential midway between that of the commutator brushes exactly as the middle point of a balancing transformer or power transformer used for the same purpose. The middle wire connection may be seen in Fig. 56.

# INDEX

D



E



F



G



H



I



K

L



M



N



O



P

| | |
|---|---|
| NITION SIMPLY EXPLAINED | By H. H. U. CROSS .. .. .. .. .. 4/- Designed to draw the Motorist's Attention to the Fundamental Principles underlying Modern Ignition Systems. 140 pp. 62 Illustrations. |
| LUMINATING AND MISSAL PAINTING | By P. WHITHARD .. .. .. .. .. 6/- A Practical Treatise on Manuscript Work, Testimonials, and Herald Painting, etc. With 2 coloured Plates. 156 pp. |
| AND READY RECKONER | By A. ARMAN .. .. .. .. .. 4/- Invaluable as an aid to the measurement of land. 6th Edition, Revised and Extended. |
| ATHE WORK | By P. N. HASLUCK.. .. .. .. .. .. 5/- A Practical Treatise on the Tools, Appliances, and Processes employed in the Art of Turning. 11th Edition, Revised and Enlarged. 240 pp. Illustrated. |
| AUNDRY CHEMISTRY | By A. HARVEY .. .. .. .. .. .. 4/- A Handbook on the Chemistry of Laundry Materials and Methods. 128 pp. |
| ETTER PAINTING MADE EASY | By J. G. BADENOCK .. .. .. .. .. 2/- A short practical Guide in which is explained a system for Ensuring Correctness in Sign Writing. 12 full-page Engravings. |
| ARBLE DECORATION | By G. H. BLAGROVE .. .. .. .. .. 3/6 A Handbook for Students, with the Terminology of British and Foreign Marbles. 28 Illustrations. |
| IASS PRODUCTION EQUIPMENT | By P. GATES .. .. .. .. .. .. 7/6 Covering the design of "Jigs, Tools, and Fixtures." "A very large amount of valuable information."—*Engineering.* 220 pp. 168 Illustrations. 22 Tables. |
| IECHANICAL DENTISTRY | By C. HUNTER .. .. .. .. .. .. 6/- A Practical Treatise on the Construction of the Various Kinds of Artificial Dentures. 8th Edn., Revised. 280 pp. 100 illus. |
| IETAL PLATE WORK | By E. G. BARRETT .. .. .. .. .. 3/6 A Text-book intended primarily for those sitting for the City and Guilds of London Institute Examination. 132 pp. 99 Illustrations. |
| ESTING MILK AND ITS PRODUCTS | By G. S. THOMSON .. .. .. .. .. 4/- In this work an attempt has been made to simplify testing so that it may be easily understood and readily adopted. 90 pp. Profusely Illustrated. |
| LOCATION OF IINERAL FIELDS | By M. H. HADDOCK .. .. .. .. .. 9/6 Written as a result of Observations in many mineral fields and a fairly wide acquaintance with mining conditions of different types. 296 pp. 213 Diagrams. 10 Plates. |
| IAGNETO MANUAL | By H. R. LANGMAN .. .. .. .. .. 7/6 For the use of Automobile Engineers, Mechanics, Apprentices, Chauffeurs, Car Owners, etc. 230 pp. Illustrated. |
| IINING CALCULATIONS | By T. A. O'DONAHUE .. .. .. .. .. 3/6 For the Use of Students preparing for the Examinations for Colliery Managers' Certificates. |
| IOTOR CAR MECHANISM AND MANAGEMENT | By E. C. M. SHEPHERD .. .. .. .. .. 3/6 A popular work on Motor Mechanism, containing many useful hints, and a section on overhauling. 170 pp. 90 Illustrations. 2nd Edition. Revised and Enlarged. |
| IOTOR TYRES | By J. C. FERGUSON .. .. .. .. .. 3/6 The volume is an investment that should save motorists many times its published price every year they follow its guidance. |
| NAVIGATION HINTS | By O. M. WATTS .. .. .. .. .. .. 7/6 With a Chapter on Weather Forecasting and 100 General Knowledge Questions and Answers. 180 pp. Illustrated. |

**PAPERMAKING** — By R. H. CLAPPERTON .. .. .. .. .. 7/6
The accepted Text-book on Paper-making, with Illustrations from Microphotographs and Plates. 3rd Edition, Revised and Enlarged. 230 pp.

**PATTERN MAKER'S HANDYBOOK** — By P. N. HASLUCK .. .. .. .. .. .. 2/-
A Practical Manual on the Construction of Patterns. 144 pp. Crown 8vo. With 100 Illustrations.

**PHOTOGRAVURE** — By C. N. BENNETT .. .. .. .. .. .. 5/-
A Little Book of Practical Instruction in the least-known and most Beautiful of all Branches of Applied Photography. 140 pp. Profusely Illustrated.

**PHYSICS AND CHEMISTRY OF MINING** — By T. H. BYROM .. .. .. .. .. .. 6/-
"This book ought to be in the hands of all mining students." —*Science and Art of Mining*.
5th Edition, Enlarged. 248 pp. Illustrated.

**PICTORIAL HOUSE MODELLING** — By E. W. HOBBS .. .. .. .. .. .. 6/-
A Practical Manual explaining how to make Models of Buildings. 196 pp. 130 Illustrations.

**PIGS AND BACON CURING** — By E. R. DAVIES .. .. .. .. .. .. 4/6
"To pig breeders and feeders the treatise is one of the most desirable of recent issues dealing with the industry."—*North British Agriculturist*. 96 pp. Illustrated.

**PLASTERING** — By W. KEMP .. .. .. .. .. .. 3/-
An attempt to deal on practical lines with an ancient and important craft, containing information on both Plain and Ornamental Plaster Work. 190 pp.

**PLUMBING (2 vols.)** — By E. G. BLAKE .. .. .. .. .. (each) 6/-
A Text-book to the Practice of the Art or Craft of the Plumber. Each Vol. 180 pp., Illustrated. (Sold separately.)
Vol. I. LEAD LAYING, &c. Vol. 2. SANITARY APPLIANCES, &c.

**POT-PLANT CULTURE** — By H. C. DAVIDSON .. .. .. .. .. .. 2/6
"Should be a useful *vade mecum* for ladies interested in the wants and welfare of plants under their own management."—*Farmer's Gazette*. New Edition. 176 pp. 65 Illustrations.

**COMMERCIAL POULTRY FARMING** — By T. W. TOOVEY .. .. .. .. .. .. 6/-
"It strikes the note of veracity throughout, and apart from being an exposition of the modern principles of poultry farming, it is full of practical hints that every poultry keeper can utilise with profit."—*Poultry*. 4th Edn., Enlarged. 160 pp. Illus.

**PROTECTION OF BUILDINGS AGAINST VERMIN** — By E. G. BLAKE .. .. .. .. .. .. 2/-
This book should supply a long-felt need, for it describes preventive measures as well as the means of destroying rats and other pests. 90 pp.

**RADIO AND HIGH FREQUENCY CURRENTS** — By E. T. LARNER .. .. .. .. .. .. 2/6
A Manual for Wireless Students, those qualifying for the P.M.G.'s Certificate, Transmitters' Licence, etc. Second Edition. Enlarged 64 pp.

**RAILWAY POINTS AND CROSSINGS** — By A. A. G. DOBSON .. .. .. .. .. .. 6/-
The Diagrams in this book are intended for the Engineer or Draughtsman who finds himself called upon to prepare plans of turnouts, etc., for places where standard types cannot be used. 96 pp. 100 Illustrations.

**ROOF CARPENTRY** — By G. COLLINGS .. .. .. .. .. .. 2/6
A useful little work designed to help the workman who has little knowledge of mathematics or the theory of the subject.

**ROTARY & MOTOR CONVERTERS** — By E. F. SMITH .. .. .. .. .. .. 7/6
For the use of those who have to do with the running of Rotary Converters, and who desire a closer acquaintance with the principles involved in their operation. 248 pp. Illustrated.